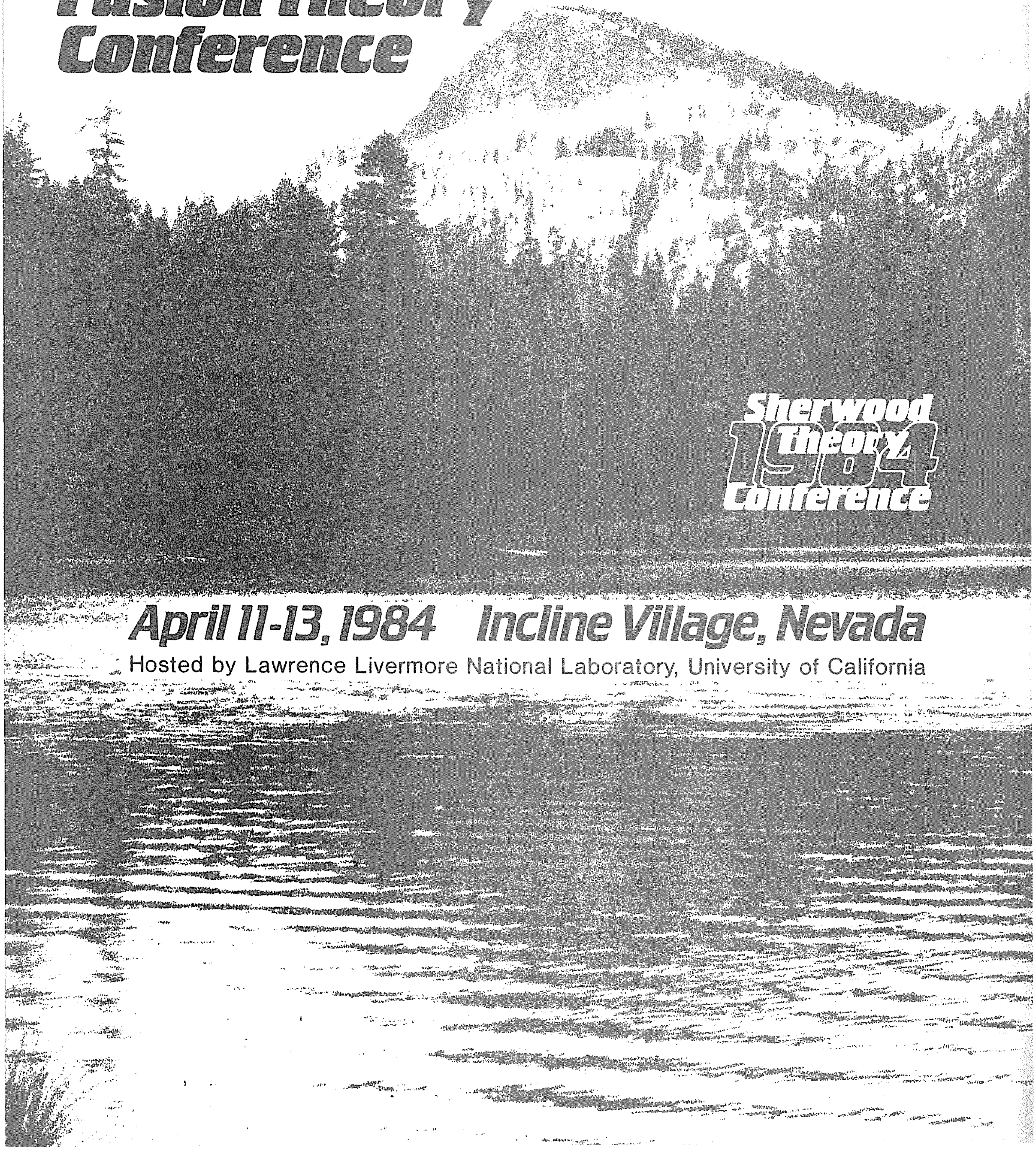
Sherwood '84

Annual Controlled Fusion Theory Conference



April 11-13, 1984 Incline Village, Nevada

Hosted by Lawrence Livermore National Laboratory, University of California

Sherwood 1984 Theory Conference

CONTROLLED FUSION THEORY CONFERENCE

April 10-13, 1984
Incline Village, Nevada

Hosted By

Lawrence Livermore National Laboratory
Livermore, California 94550

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GENERAL INFORMATION

- There were 276 papers submitted, of which 29 were selected for oral presentation.
- All oral sessions will be held in the Tahoe Grand Ballroom. Each talk will be 20 minutes in length plus 5 minutes for discussion.
- Poster sessions will be held in the Prospector and El Dorado rooms, and in the Lower Lobby of the Grand Ballroom. The Prospector and El Dorado rooms are located behind the Grand Ballroom and can be reached through the Lower Lobby.
- Breakfast is included in the registration fee and will be served from 7:15 to 8:30 a.m. in the Lakeside Room, across the road from the main hotel building.
- Beverages will be served in the Lower Lobby: coffee and tea during the morning sessions; beer and soft drinks during the afternoon and evening sessions.
- The information desk at the registration area has information about skiing, sightseeing, tours, and restaurants.
- A hospitality room and a room for children accompanied by parents are available; inquire at the information desk. Child care service can be arranged through the hotel concierge.
- Any requests for special meetings should be made with D. Richards or J. Wikkerink at the registration desk.

ORAL AND POSTER SESSION SCHEDULE

Tuesday, April 10, 1984

6:00 - 9:00 p.m. -- Registration
Tahoe Grand Ballroom

8:00 - 10:00 p.m. -- Reception
Lakeside Room

Wednesday, April 11, 1984

8:20 - 8:30 a.m. -- WELCOME

Oscar Buneman Oral Session

1A 8:30 - 9:20 (Review Paper)

Oral Sessions		Poster Sessions	
1B	9:20 - 9:45*	1P	9:30 - 10:45
1C	10:30 - 12:15	1Q	11:00 - 12:15

12:15 - 2:00 p.m. -- LUNCH

1D	2:00 - 3:15	1R	2:00 - 3:30 **
1E	3:45 - 5:00	1S	4:00 - 5:30

Thursday, April 12, 1984

Oral Sessions		Poster Sessions	
2A	8:30 - 9:20 (Review Paper)		
2B	9:20 - 9:45 *	2P	9:30 - 10:45
2C	10:30 - 12:15	2Q	11:00 - 12:15

12:15 - 7:30 p.m.
AFTERNOON FREE

2D	7:30 - 8:45 P.M.	2R	7:30 - 9:00 P.M.**
2E	9:00 - 10:15 P.M.	2S	9:15 - 10:45 P.M.

Friday, April 13, 1984

Oral Session		Poster Sessions	
3A	8:30 - 9:45 *	3P	8:30 - 10:15
3B	10:30 - 12:15	3Q	10:30 - 12:15

* Coffee, tea, will be available from 9:15 a.m. - noon
** Beer and soft drinks will be available from 2:00 - 5:30 p.m. on Wednesday and from 7:30 - 10:30 p.m. on Thursday.

1984 SHERWOOD THEORY CONFERENCE
ANNUAL CONTROLLED FUSION THEORY CONFERENCE
APRIL 10-13, 1984

TUESDAY, APRIL 10

6:00 - 9:00 PM -- REGISTRATION — TAHOE GRAND BALLROOM
8:00 -10:00 PM -- RECEPTION — LAKESIDE ROOM

WEDNESDAY, APRIL 11

7:45 - 4:30 REGISTRATION

8:20 - 8:30 WELCOME (R. Cohen)

1A THE Oscar Buneman ORAL SESSION 8:30 - 9:20 (CHAIR: R. Kulsrud)

1A1. The Inner Magnetosphere of Jupiter--The Io Plasma Torus. J. Belcher.

1B ORAL SESSION 9:20 - 9:45 (CHAIR: R. Kulsrud)

1B1. Stabilization of an Axisymmetric Tandem Mirror. H. L. Berk, M. N. Rosenbluth, H. V. Wong, and T. M. Antonsen, Jr.

1C ORAL SESSION 10:30 - 12:15 (CHAIR: P. Catto)

1C1. Rapidly Convergent Algorithms for 3-D Equilibria in Tandem Mirrors and Stellarators in the Paraxial Approximation. B. McNamara.
1C2. Dissipative Trapped Particle Modes in Tandem Mirrors. W. M. Nevins, R. H. Cohen, J. A. Byers, H. L. Berk, M. N. Rosenbluth, and H. Ramachandran.
1C3. Boundary-Layer Transport in Tandem Mirrors with Axisymmetric Throttles. R. H. Cohen, S. P. Auerbach, and I. B. Bernstein.
1C4. Tandem Mirror Transport and Induced Azimuthal Variation of the Electrostatic Potential. X. S. Lee, J. R. Myra, P. J. Catto, and G. L. Francis.

1P POSTER SESSION 9:30 - 10:45

1P1. Validity of Mixing Length Saturation Theory and its Implication for Anomalous Thermal Transport in RFP. Z. G. An, P. H. Diamond, and T. H. Chiueh.
1P2. Survey of Theories of Turbulence and Anomalous Transport in Tokamaks. P. C. Liewer.
1P3. Current-Drive by Fast Waves. D. K. Bhadra and P. L. Andrews.
1P4. Fluid Description of Microtearing Turbulence in a Sheared Slab. G. G. Craddock, P. H. Diamond, and P. W. Terry.
1P5. A Three-Dimensional Model for Relaxation Phenomena. A. E. Dabiri, D. D. Schnack, and R. A. Gerwin.
1P6. Injection and Trapping of an Ion Ring in a Compact Torus Configuration. P. M. Lyster and R. N. Sudan.

1P7. Helical Axis Stellarator Equilibria. A. E. Koniges and J. L. Johnson.
1P8. Characterization of Stochastic Field Lines in RFP Plasmas. H. Gurol and D. D. Schnack.
1P9. Nonlinear Fluctuations of an Ideal Two Fluid Model: Stochastic Transition vs. Transport? H. A. Rose.
1P10. Low-n Toroidal Shear Alfven Waves. M. S. Chance and C. Z. Cheng.
1P11. Nonlinear Evolution of Drift Tearing Modes. B. D. Scott, A. B. Hassam, and J. F. Drake.
1P12. Numerical Simulation of Electromagnetic Trapped Electron Turbulence in Tokamaks. R. E. Waltz.
1P13. Simulation of the Evolution of a Spheromak. A. G. Sgro, G. Marklin, and A. A. Mirin.
1P14. Electron Heating by Waves at Ion Frequencies. A. Fruchtman and H. Weitzner.
1P15. Simulation of Impurity Transport in the ISX-B Tokamak with Directed Neutral Beam Heating. E. C. Crume and D. E. Arnurius.
1P16. Stochastic Motion of Mirror-Confined Electrons by a Frequency-Modulated Wave. A. Ram, M. Mauel, and A. Bers.
1P17. An Obstacle to Predictability. S. W. McDonald, C. Grebogi, E. Ott, and J. A. Yorke.
1P18. Simulation of Mode Induced Beam Loss in Tokamaks. R. Hay, R. B. White, and L. Chen.
1P19. Enhanced Neoclassical Diffusion of Nonresonant Particles in a Bumpy Torus. R. L. Miller, C. S. Chang, and D. K. Lee.
1P20. Resistive Ballooning in Toroidal RFP's. R. Y. Dagazian and M. S. Chance.
1P21. Onset of Stochasticity and the Diffusion Approximation in Drift Waves. D. F. Escande and W. Horton.
1P22. Asymptotic Analysis of rf-heated Collisional Plasma. N. J. Fisch and C. F. F. Karney.
1P23. An Incompressible, Pseudospectral Computational Model for the Reversed-Field Pinch. B. G. Small and D. D. Schnack.
1P24. Current Generation in Stellarators. J. T. Hogan, L. Ibanez, and H. Grad.
1P25. Electron Transport of a Quiescent Plasma With a Finite Inhomogeneity. K. Matsuda.

1Q POSTER SESSION 11:00 - 12:15

1Q1. Higher Order Mode Conversion Problems. D. G. Swanson.
1Q2. The Effect of Hall Terms on Resistive g-Modes in a Reversed Field Pinch. A. A. Mirin and N. J. O'Neill.
1Q3. Transport Associated with the Collisionless Detrapping/ Retrapping of Orbits in a Nonaxisymmetric Torus II. R. H. Fowler, J. A. Rome, and K. C. Shaing.
1Q4. Atomic Processes for Diagnosing Tokamak Plasmas. S. Suckewer.
1Q5. Free Boundary Stellarator Expansion MHD Equilibrium and Stability Calculations. J. A. Holmes, B. A. Carreras, L. A. Charlton, H. R. Hicks, and V. E. Lynch.
1Q6. Efficient Magnetic Analysis of Noncircular Tokamaks. L. L. Lao, H. St John, R. D. Stambaugh, W. Pfeiffer, and R. E. Stockdale.
1Q7. Ohm's Law Re-Examined for Large Mean Free Paths; A Preliminary Implication for the Field-Reversed Configuration. R. A. Gerwin and W. Riesenfeld.
1Q8. Aurora. B. L. Smith and H. Okuda.
1Q9. Lower Hybrid Heating Studies in the Presence of Impurity Generation in the Alcator C Tokamak. M. Porkolab, P. T. Bonoli, and R. Englade.
1Q10. Linear Non-Stochastic Heating by Perpendicularly Propagating Electrostatic Waves. T. Katsouleas and J. M. Dawson.
1Q11. Resonant Transport of the Plasma Ions in a Bumpy Torus. C. S. Chang.
1Q12. Canonical Magnetic Hamiltonian. A. H. Boozer.
1Q13. Neoclassical Ion Transport through the Separatrix in Divertor Tokamaks. F. L. Hinton and M. S. Chu.
1Q14. Analytic Representation for Force-Free Fields in an RFP with Four-Node Poloidal Divertor. J. S. Sariff, L. Turner, S. C. Prager, and J. C. Sprott.
1Q15. Electron Response to Electromagnetic Perturbations in Toroidal Plasmas. R. Carrera and R. D. Hazeltine.

1Q16. Configuration Dependence of the H-Mode. R. W. Moore, L. C. Bernard, and M. S. Chu.
1Q17. An Algorithm for Finding the Magnetic Axis. V. Faber, A. B. White, Jr., and G. M. Wing.
1Q18. Suppression of Spectral Pollution by Angle Renormalization. W. A. Cooper and S. P. Hirshman.
1Q19. MHD Equilibrium Studies of a Poloidal Divertor Tokamak using the Chodura-Schluter Method. E. Uchimoto, J. D. Callen, L. Garcia, and B. A. Carreras.
1Q20. An Analysis of a Low Frequency Oscillating Field Current Drive of an RFP. D. A. Baker, R. F. Gribble, and K. F. Schoenberg.
1Q21. Steady State Solution of the Fokker-Planck Equation Combined with Unidirectional Quasilinear Diffusion under Detailed Balance Conditions. K. Hizanidis.
1Q22. Strong Turbulent Theory of Alfven Waves. C. Y. Chen and S. M. Mahajan.
1Q23. Deuterium Recycling in ZT-40M Reversed-Field Pinch. T. E. Cayton.
1Q24. The Early Time Behavior of Lower Hybrid Current Drive. R. Englade and P. T. Bonoli.
1Q25. Quasilinear Evolution of Tearing Modes. W. Horton, T. Tajima, and R. M. O. Galvao.

12:15 - 2:00 LUNCH

1D ORAL SESSION 2:00 - 3:15 (CHAIR: J. Schwarzmeier)

1D1. Nonlocal DC Electrical Conductivity of a Lorentz Plasma in a Stochastic Magnetic Field. A. R. Jacobson and R. W. Moses.
1D2. Sustained Reversal of a Reversed Field Pinch. A. Y. Aydemir and D. C. Barnes.
1D3. Three-Dimensional Studies of Coherent Resistive MHD Activity in the Reversed-Field Pinch. D. D. Schnack, D. C. Baxter, E. J. Caramana, R. A. Nebel, R. Watt, and G. A. Wurden.

1E ORAL SESSION 3:45 - 5:00 (CHAIR: D. Ross)

1E1. The Dynamo Effect in Fusion Plasmas. H. R. Strauss.
1E2. Drift Wave Turbulence and Experimental Confinement Scaling. F. W. Perkins.
1E3. Implications of Kinetic Instabilities for Anomalous Transport Modelling. W. M. Tang and B. Coppi.

1R POSTER SESSION 2:00 - 3:30

1R1. High Current Ignition Experiments. L. Sugiyama.
1R2. Ponderomotive Force Stabilization of Interchange-Ballooning Modes in Axisymmetric Mirrors. J. R. Myra and D. A. D'Ippolito.
1R3. Calculation of Multi-Ion Trapping Rates in Tandem Mirror End Cells. R. S. Devoto, A. A. Mirin, and E. J. Horowitz.
1R4. High Frequency Stability of the Precessional Mode in a Hot Electron Symmetric Tandem Mirror. K. T. Tsang and X. S. Lee.
1R5. Excitation of Ion Bernstein Modes from Density Fluctuations during ICRF Heating of Tokamaks. S. N. Antani, G. J. Morales, and B. D. Fried.
1R6. Electrostatic Confinement in a Bumpy Torus with Hot Electron Rings. A. M. El Nadi.
1R7. Resistive MHD-Like Equations in the Banana-Plateau Collisionality Regime. J. D. Callen and K. C. Shaing.
1R8. Low Frequency Stability of Axisymmetric Tandems with Hot Electrons. R. P. Freis, B. I. Cohen, J. H. Hammer, and T. B. Kaiser.
1R9. Influence of Ion Cyclotron Heating on Interchange Stability. B. I. Cohen, T. D. Rognlien, and W. F. Cummins, Jr.

1R10. Modeling of ICRH Heating in TMX-U. R. B. Campbell and G. Dimonte.
1R11. Nonlinear Saturation of Single Mode Dissipative Trapped Particle Instability. S. Kim and A. K. Sen.
1R12. Physics Overview of the ELMO Bumpy Square. N. A. Uckan, L. W. Owen, L. A. Berry, C. L. Hedrick, and D. A. Spong.
1R13. Incompressible M.H.D. Modes in Toroidal Geometry. L. A. Charlton, B. A. Carreras, H. R. Hicks, J. A. Holmes, and V. E. Lynch.
1R14. Energetic Electrons in EBT. S. Hamasaki, N. A. Krall, and J. L. Sperling.
1R15. Equilibrium and Axisymmetric Stability of the Columbia High-beta Tokamak. J. DeLucia.
1R16. How Fast is Fast Magnetic Reconnection Across an X-Type Neutral Point? D. Biskamp.
1R17. Fokker-Planck Modeling of Electron Cyclotron Heating and Direct Particle Loss in EBT and ELMO Bumpy Square. G. L. Chen, D. B. Batchelor, and Y. Matsuda.
1R18. Computer Evaluation of the Magnetic Field Line Hamiltonian. G. Kuo-Petravic and A. H. Boozer.
1R19. Cross Magnetic Field Transport due to like Particle Collisions. T. M. O'Neil.
1R20. Lower Hybrid Wave Propagation in a Stochastic Plasma Background. W. Grossmann and R. Spigler.
1R21. Adiabatic Limit in an Oscillating Doublet. M. Kress and H. Grad.
1R22. Transport in Stellarators: Some Special Features. D. D. M. Ho and R. M. Kulsrud.
1R23. Maximum Entropy and Direct Fourier Spectral Observations of Fluctuations in Turbulent Simulation Plasma. R. H. Berman and J. N. Leboeuf.
1R24. FLR-Corrected Collision Operator: An Alternative Approach to Solving the Fokker-Planck Equation. S. P. Auerbach.
1R25. Studies on D-T Alpha-Driven Instability in Tandem Mirror Reactor. S. K. Ho and G. H. Miley.

1S POSTER SESSION 4:00 - 5:30

1S1. Low Frequency Stabiilty in Tandem Mirrors. L. LoDestro.
1S2. Energy Limiting and Temporal Evolution of Hot Electrons in TMX-U. T. D. Rognlien and Y. Matsuda.
1S3. Stabilization of Ballooning Modes in Axisymmetric Mirror by Hot Electron Rings and RF Electric Fields. H. Sanuki, G. J. Morales, and B. D. Fried.
1S4. Electrostatic Instabilities Associated with the Axial Shear of the Azimuthal E x B Rotation in Collisionless and Collisional Plasmas. B. Lane.
1S5. The Dynamics of the Collisionless Tearing Mode. S. C. Cowley and R. M. Kulsrud.
1S6. Ideal MHD Ballooning Instability and Scaling Law for Confinement. J. W. Connor, J. B. Taylor, and M. F. Turner.
1S7. Upper-Hybrid and Cyclotron Resonances in the Presence of an Ambipolar Electric Field. S. A. Prasad, G. J. Morales, and B. D. Fried.
1S8. Collective Enhancement of Radial Transport. D. L. Eggleston, T. M. O'Neil, and J. H. Malmberg.
1S9. Enhancement of the Reaction Rate by ICRF Heating. V. B. Krapchev.
1S10. Stability of Drift Waves in Stellarator and Tokamak Geometries. J. N. Leboeuf, T. Tajima, and R. D. Sydora.
1S11. Multiple Hamiltonian Structure of Fluid and Kinetic Theory. J. D. Meiss and P. J. Morrison.
1S12. Coupling of ICRF Power from Dielectrically Loaded Waveguides to Plasmas. J. J. Thomson, R. B. White, and S. Freije.
1S13. Study of Electron Transport Utilizing Results of the ECH Experiment on PDX. A. H. Kritz, D. R. Mikkelsen, A. Cavallo, and H. Hsuan.
1S14. A Conceptual Design of a Radioactivity-Free 3He Fuel Processing Station in a d-3He Neutron-Lean Fusion Power Plant. G. W. Shuy.
1S15. Numerical Modeling of Poloidal Divertors. M. Petravic, S. Lieberson-Heifetz, D. Heifetz, and D. E. Post.
1S16. Axisymmetric Stability and Control in Toroidal Devices. N. Pomphrey, S. C. Jardin, H. Takahashi, K. M. Ling, and Y. C. Sun.

1S17. Hall Effects on Tearing Modes. S. C. Zhao and Y. P. Pao.
1S18. Stabilization of the Spheromak Tilt Instability. R. N. Sudan.
1S19. Electrostatic and Magnetostatic Tandem Mirror Equilibria from Realistic Plasma Distributions. D. V. Anderson and B. M. Boghosian.
1S20. Rotation and Impurity Flow Reversal in Tokamak Plasmas with Neutral Beam Injection. W. M. Stacey, Jr., A. W. Bailey, and D. J. Sigmar.
1S21. Paraxial Propagation Approximation for Fast Magnetosonic Waves in Tokamak Plasmas. C. K. Phillips, F. W. Perkins, and D. Q. Hwang.
1S22. Formation Studies for the New Maryland Spheromak (MS). P. N. Guzdar, K. W. Whang, J. M. Finn, and A. Bondeson.
1S23. Singular Behavior of Three-Dimensional Toroidal Equilibria. J. M. Greene, F. J. Helton, and L. L. Lao.
1S24. Inverse Mapping Algorithm for Moments Formulation of MHD Equilibria. W. A. Houlberg, S. P. Hirshman, and S. E. Attenberger.
1S25. Analytic Moment Method Calculations of the Drift Wave Spectrum. D. R. Thayer and K. Molvig.

THURSDAY, APRIL 12

2A ORAL SESSION 8:30 - 9:20 (CHAIR: H. Strauss)

2A1. Theory and Simulation of the Fishbone Instability. R. B. White.

2B ORAL SESSION 9:20 - 9:45 (CHAIR: H. Strauss)

2B1. Resistive Fluid Turbulence and Energy Confinement. J. B. Taylor and J. W. Connor.

2C ORAL SESSION 10:30 - 12:15 (CHAIR: B. Carreras)

2C1. Theory of Turbulent Processes in the Tokamak Edge. P. W. Terry and P. H. Diamond.
2C2. Reduced Equations for Finite Beta Resistive Modes in Tokamak. R. Izzo, D. A. Monticello, J. DeLucia, W. Park, H. R. Strauss, and S. C. Jardin.
2C3. 3-D MHD Stability of High-Beta Free-Boundary Plasmas with Finite Edge-Pressure-Gradient and Limiter Stabilization. J. K. Lee, R. E. Waltz, N. Ohyabu, R. W. Moore, M. S. Chu, and L. C. Bernard.
2C4. An Ultimate Beta-Limit for Macroscopically Stable Tokamaks. J. J. Ramos.

2P POSTER SESSION 9:30 - 10:45

2P1. Numerical Evaluation of Collisional Trapped-Particle Modes in Tandem Mirrors. H. Ramachandran, R. H. Cohen, and W. M. Nevins.
2P2. Analysis and Simulation of the Trapped Particle Mode in Tandem Mirrors. J. A. Byers and W. M. Nevins.
2P3. Feedback Control of Trapped Particle Modes in Tandem Mirrors. A. K. Sen.
2P4. Stabilization of Resistive Ballooning Modes by Electron Thermal Conductivity. A. K. Sundaram, A. Sen, and P. K. Kaw.
2P5. Thermal Barrier Pumping and Alpha Control using Low Energy Neutral Beams in a TARA Reactor. X. Z. Li, J. Kesner, R. Potok, and J. Strohmayer.
2P6. Evidence of Discrete Alfven Waves in a Plasma Column. F. Brunel, J. N. Leboeuf, and S. M. Mahajan.
2P7. Monte Carlo Calculations for the ISX Pumped Limiter. K. Evans, Jr., D. Heifetz, D. E. Post, and P. Mioduszewski.

2P8. Neoclassical Tokamak Transport with Toroidal Flow. W. Kerner and H. Weitzner.
2P9. Bounce-Averaged Monte-Carlo Calculations of Ripple Transport. W. N. G. Hitchon, C. D. Beidler, and J. L. Shohet.
2P10. Simulation of Injected Impurities on TEXT. J. C. Wiley, W. H. Miner, Jr., and D. W. Ross.
2P11. Destabilization of Ideal Ballooning Modes by Energetic Trapped Particles. J. W. Van Dam, M. N. Rosenbluth, C. S. Liu, and T. M. Antonsen, Jr.
2P12. Destabilization of Ballooning-Precessional Mode in Hot-Electron Plasmas. B. Hafizi, R. E. Aamodt, and K. T. Tsang.
2P13. Nonlinear Interaction of Tearing Modes and Dynamo in the Reversed Field Pinch. P. H. Diamond and Z. G. An.
2P14. Electron Microinstabilities in Relativistic Mirror Plasmas. G. R. Smith and Y-J. Chen.
2P15. FLARE: A 3-D Linearized Compact Torus Stability Code. Z. Mikic and E. C. Morse.
2P16. Study of Stellarator Devices by Expansion Techniques. J. L. Johnson, G. Rewoldt, G. Kuo-Petravic, and A. H. Boozer.
2P17. The Dispersion Functional for Multidimensional Equilibria and its Application to Field-Reversed Configurations. D. C. Barnes, H. R. Lewis, J. L. Schwarzmeier, and C. E. Seyler.
2P18. Diffusion in the Quantum Standard Map with Noise. J. D. Hanson, E. Ott, and T. M. Antonsen, Jr.
2P19. Magnetic Field Effects on Pellet Ablation in High Temperature Plasmas. G. Zavala and T. Kammash.
2P20. Nonlinear Stability Analysis via the Method of Invariant Manifolds and Normal Forms. Y. M. Treve.
2P21. The Effects of Focusing on Lower Hybrid Waves. A. H. Glasser.
2P22. Saturation and Diffusion of Drift Instabilities. W. W. Lee and W. M. Tang.
2P23. Ballooning Instabilities due to Energetic Trapped Particles. J. Weiland and L. Chen.
2P24. Non-Local Transport in Tokamaks. J. A. Rome and R. H. Fowler.
2P25. Quasi-linear Dynamo from Resistive Pressure-Driven Instabilities. K. A. Werley, R. A. Nebel, and G. H. Miley.

2Q POSTER SESSION 11:00 - 12:15

2Q1. Electron-Cyclotron Maser Instability in Magnetic Mirror Machines. H. K. Wong, J. D. Gaffey, Jr., and C. S. Wu.
2Q2. Analytic Stellarator Equilibria with Ellipticity. W. H. Choe and J. P. Freidberg.
2Q3. Nonlinear Depletion of Lower-Hybrid Waves. J. M. Wersinger.
2Q4. An Analysis of Single-Wave Particle Orbits Based on Constants of Motion with Application to Simulations of the Alfven Ion-Cyclotron Instability. N. F. Otani.
2Q5. The Effect of Tensor Viscosity on Magnetosonic Waves. G. Marklin.
2Q6. RF Induced Transport in ICRF Minority Heating. V. S. Chan, S. C. Chiu, and S. K. Wong.
2Q7. Density Limit for Lower Hybrid Current Drive. D. C. Eder and E. J. Valeo.
2Q8. Single-Cell Mirror with Pumped Thermal Barriers. J. F. Santarius.
2Q9. Explosive Coalescence. T. Tajima, J. I. Sakai, and F. Brunel.
2Q10. MHD Studies of TFTR Discharges. W. Park, D. A. Monticello, M. Bell, R. Izzo, K. McGuire, and R. B. White.
2Q11. A d-3He Neutron-Lean Fusion Reactor and a 3He-Breeder System. D. Dobrott, G. W. Shuy, A. E. Dabiri, H. Gurol, B. Kirstein, and S. Tamor.
2Q12. Stabilizing Influence of Hot Beam Ions on Ballooning Modes in Tokamaks. G. Rewoldt and W. M. Tang.
2Q13. Thermal Conductivity of Electrons through a Potential Barrier. M. S. Chu, R. W. Harvey, F. L. Hinton, and S. K. Wong.
2Q14. Perturbation Theory Analysis of Ion Cyclotron Waves in EBT. N. T. Gladd.
2Q15. Matrix Elements of Linearized Fokker-Planck Operator. S. K. Wong.
2Q16. Nonlinear Landau Damping of Purely Perpendicular Bernstein Modes. S. Riyopoulos.
2Q17. Heat Pulse Propagation to Determine the Electron Diffusivity Chi e. K. McGuire, J. D. Callen, J. DeLucia, K. Hill, R. Izzo, and D. A. Monticello.

2Q18. Action Jumps and Their Relation to Strong Turbulence Theory. J. L. Tennyson, J. R. Cary, and D. F. Escande.
2Q19. Modeling Ambipolar Potential Formation due to ICRF Heating Effects on Electrons. J. W. Johnson, J. D. Callen, and N. Hershkowitz.
2Q20. The Big Dee Upgrade of Doublet III. F. J. Helton, J. M. Greene, J. L. Luxon, and M. A. Mahdavi.
2Q21. Propagation and Absorption of Electromagnetic Waves in Fully Relativistic Plasmas. R. C. Goldfinger, D. B. Batchelor, and H. Weitzner.
2Q22. Particle Loss Rates from Electrostatic Wells of Arbitrary Mirror Ratios. P. J. Catto and X. Z. Li.
2Q23. The Spectrum of the MHD and Kinetic Alfven Waves in a Cylindrical Tokamak. W. I. Van Rij, G. Vahala, and D. J. Sigmar.
2Q24. A Study of Mode Coupling at Omega = 2 Omega ci. M. M. Shoucri, V. Fuchs, L. Harten, and A. Bers.
2Q25. Use of Local Dispersion Relation around the Mode Conversion Layer and Connection with WKB Theory. S. C. Chiu.

12:15 - 7:30 PM AFTERNOON FREE

2D ORAL SESSION 7:30 - 8:45 PM (CHAIR: T. Kaiser)

2D1. Studies of Acceleration of Compact Toroids. C. W. Hartman, J. H. Hammer, and J. L. Eddleman.
2D2. Collisionless Neoclassical Nonresonant Transport in Bumpy Tori. D. E. Hastings.
2D3. Ballooning Modes in the ELMO Bumpy Square Configuration Using the Generalized Kinetic Energy Principle. D. A. Spong, C. L. Hedrick, and J. W. Van Dam.

2E ORAL SESSION 9:00 - 10:15 PM (CHAIR: J. Hammer)

2E1. Collective Modes in Spin Polarized Plasmas. F. Pegoraro, B. Coppi, S. C. Cowley, P. Detragiache, R. M. Kulsrud, and J. J. Ramos.
2E2. Alpha Effect and Beta Effect Dynamos. D. Montgomery and H. Chen.
2E3. A Study of the Nonlinear Modulational Instability. E. Tracy, H. H. Chen, and Y. C. Lee.

2R POSTER SESSION 7:30 - 9:00 PM

2R1. Calculation of HELIAC Vacuum Magnetic Field Configurations. A. I. Shestakov and A. A. Mirin.
2R2. Analytic Dynamo Model for the Reversed-Field Pinch. S. Buchsbaum, D. Dobrott, and D. D. Schnack.
2R3. Small-Scale Structures in Convective Two-Dimensional Benard Turbulence. C. G. Schultz and R. N. Sudan.
2R4. Nonlinear Evolution of Microtearing Modes. L. Garcia, B. A. Carreras, and H. R. Hicks.
2R5. Drift Turbulence in a Sheared Magnetic Field. M. Walter and D. Biskamp.
2R6. Resistive Interchange Instability in 3D Code Stellarator Equilibria. J. Nuhrenberg and R. Grobmann.
2R7. Determination of the Boundaries of Stochastic Regions of Phase Space for Strongly Perturbed Nonlinear Oscillators. R. V. Jensen.
2R8. Long Pulse Evolution of Elongated, Rippled High-Beta Tokamaks. L. Ibanez, H. Grad, A. Bayliss, and J. T. Hogan.
2R9. Comparison of Experimental and Numerical FRC Equilibria. M. Tuszewski and R. L. Spencer.
2R10. The Rotational Instability in Field-Reversed Configurations. R. L. Spencer and D. S. Harned.
2R11. Instabilities Excited by an Energetic Ion Beam and Electron Temperature Anisotropy in Tandem Mirrors. J. D. Gaffey, Jr., E. H. Da Jornada, and D. Winske.
2R12. Hamiltonian Studies of Compressible Reduced MHD. P. J. Morrison and R. D. Hazeltine.

2R13. Computer Simulation of RF Stabilization of the Flute Instability. I. M. A. Gledhill and J. M. Dawson.
2R14. Poloidal Flux in Stellarators and Torsatrons. J. L. Shohet, D. T. Anderson, W. N. G. Hitchon, and K. D. McLenithan.
2R15. A Model Distribution Function for Thermal Barrier Electrons. M. E. Rensink.
2R16. Ion Cyclotron Resonance Heating by Means of the Fast Wave in a Longitudinally Inhomogeneous Magnetic Field. C. N. Lashmore-Davies, V. Fuchs, R. A. Cairns, and M. M. Shoucri.
2R17. Transport Simulations of the PDX/ASDEX H-Mode. M. H. Redi, C. E. Singer, D. R. Mikkelsen, F. G. P. Seidl, and W. D. Langer.
2R18. ICRF Catalyzed Fusion Reactivity Enhancement. G. D. Kerbel and M. G. McCoy.
2R19. Efficiency Limit for Current Drive by Fast Waves. C. F. F. Karney and N. J. Fisch.
2R20. A Simple Model for Lower Hybrid Current Drive in Tokamaks. P. L. Andrews, V. S. Chan, and C. S. Liu.
2R21. Ballooning Instabilities as the Cause of H Alpha Spikes. W. X. Qu and J. D. Callen.
2R22. Analysis of Localized Interchange Modes in PDX. J. Manickam, K. McGuire, and A. E. Miller.
2R23. Determination of Multiple Tokamak Equilibria. D. J. Elkin.
2R24. Optimum Stability Limits of Bean Shaped Plasmas. M. W. Phillips, B. K. McKee, S. L. Mendelsohn, A. M. M. Todd, M. S. Chance, R. C. Grimm, A. E. Miller, and M. Okabayashi.
2R25. Cubic Turbulence in Fusion Plasmas. D. R. Nicholson and S. Guo-Zheng.

2S POSTER SESSION 9:15 - 10:45 PM

2S1. Approximate Flux Conserving Stellarator. B. A. Carreras, H. R. Hicks, J. A. Holmes, and V. E. Lynch.
2S2. Effects of Cold Gas on the Operation of a Tandem Mirror. Y. Matsuda, D. E. Baldwin, and R. A. Jong.
2S3. Stability of the Radial Electric Field in a Nonaxisymmetric Torus. K. C. Shaing.
2S4. Variational Method for Toroidal Equilibria with Imperfect Flux Surfaces. A. Bhattacharjee.
2S5. Effects of Helical Fields on Reversed Field Pinch. C. Chu, W. Bard, and R. W. Moore.
2S6. Models of Energy Confinement in Tokamaks. W. Pfeiffer, R. E. Waltz, R. W. Moore, and C. S. Liu.
2S7. Ideal Magnetohydrodynamic Equilibrium and Stability Studies of a Toroidal System with Arbitrary Helical Fields. G. Berge, W. H. Choe, and J. P. Freidberg.
2S8. Trapped Particle Destabilization of the Internal Kink Mode. R. B. White, L. Chen, F. Romanelli, and R. Hay.
2S9. Lagrangian and Hamiltonian Theory of Gyrokinetic Equations. R. G. Littlejohn.
2S10. CTR: Controlled or Catastrophic Thermonuclear Reactors? J. R. McNally, Jr.
2S11. The Effect of Finite Beta on Stellarator Transport. H. E. Mynick.
2S12. Toroidal Shear Alfven Instability due to Energetic Particles. C. Z. Cheng and L. Chen.
2S13. Theory of Weakly Collisional Kinetic Alfven Waves in Sheared Magnetic Fields. T. S. Hahm, L. Chen, and Y. C. Lee.
2S14. Nonlinear Evolution of Tearing Modes in Cylindrical Plasmas. Y. P. Pao and S. C. Zhao.
2S15. Effect of Radial Structure of Electrostatic or Magnetic Perturbations on the Diffusion of Test Particles in a Sheared Magnetic Field. F. Pohl and D. Biskamp.
2S16. Nonlinear Saturation of the Hot Electron Interchange Mode. M. Rosenberg, N. A. Krall, and R. R. Dominguez.
2S17. Plasma Injection Across Transverse and Curved Magnetic Fields. J. K. Koga, J. L. Geary, T. Tajima, and N. Rostoker.
2S18. Numerical Simulation of Plasma Potential Control Operation of TMX-U. J. M. Gilmore and E. B. Hooper.
2S19. Compressional Alfven Wave for Heating and Current Drive in the Presence of Alpha Particles. Y. M. Li, S. M. Mahajan, and D. W. Ross.
2S20. The Reliability of Initial Value MHD Calculations of Tokamak Disruptions. H. R. Hicks, B. A. Carreras, L. Garcia, and J. A. Holmes.
2S21. A Consistent Drift Kinetic Theory. P. N. Hu.
2S22. Atomic Processes and Energy Loss in Diverted Edge Plasmas. W. D. Langer, R. K. Janev, D. E. Post, and K. Evans, Jr.

2S23. Motion of Charged Particles in Stochastic Magnetic Fields. M. E. Fenstermacher.
2S24. Nonlinear Theory of Electromagnetic Trapped Electron Modes. R. R. Dominguez, R. W. Moore, L. C. Bernard, and C. S. Liu.

FRIDAY, APRIL 13

3A ORAL SESSION 8:30 - 9:45 (CHAIR: R. Moore)

3A1. Magnetic Islands in Three-Dimensional Toroidal Plasma. J. R. Cary and M. Kotschenreuther.
3A2. Formation of Magnetic Islands in Three-Dimensional MHD Equilibria. A. H. Reiman and A. H. Boozer.
3A3. Theory of Plasmas Near the Lawson Limit. B. Coppi.

3B ORAL SESSION 10:30 - 12:15 (CHAIR: W. Nevins)

3B1. Resonance Localization and Poloidal Electric Field due to Cyclotron Wave Heating in Tokamak Plasmas. J. Y. Hsu, V. S. Chan, R. W. Harvey, R. Prater, and S. K. Wong.
3B2. Second Harmonic Electron Cyclotron Heating. M. D. Carter, D. B. Batchelor, and J. D. Callen.
3B3. The Cold Plasma Model and Lower Hybrid Heating. H. Weitzner.
3B4. The Calculation of Fast Wave Fields in Tokamak Geometry. R. J. Kashuba and P. L. Colestock.

3P POSTER SESSION 8:30 - 10:15

3P1. Nonlinear Stability Conditions for a Relativistic Multifluid Plasma. D. D. Holm.
3P2. Monte Carlo Simulation of Lower Hybrid Wave Scattering in the Alcator C Tokamak. P. T. Bonoli, R. L. Watterson, and M. Porkolab.
3P3. Stationary Fluid Model of Divertor Flows from the Scrapeoff Layer. R. Morse, D. Morrison, and G. Sowers.
3P4. Dynamic Solutions of the Fluid Equations for Divertor and Scrapeoff Solutions. D. Morrison, R. Morse, and G. Sowers.
3P5. Absorption, Reflection, and Mode Coupling at the Second Cyclotron Resonance in a Weakly Relativistic, Inhomogeneous Plasma. K. Imre, H. Weitzner, and D. B. Batchelor.
3P6. Electron Transports and Microscopic MHD Turbulence. A. Hasegawa.
3P7. A Theoretical Model for Interpreting Confinement in Field-Reversed Configuration Experiments. L. Steinhauer.
3P8. Hamiltonian Representation of Helical Force-Free Magnetic Fields. L. Turner.
3P9. Transport Description of the Risetime of Sawtooth Oscillations in Reversed-Field Pinches. R. A. Nebel, K. A. Werley, and G. A. Wurden.
3P10. Self-Consistent Hamiltonian and Dissipative Formulations of Nonlinear Processes. A. N. Kaufman, P. L. Similon, and B. M. Boghosian.
3P11. Comparison of 3-D Moments and Finite Difference Inverse MHD Equilibrium Codes. S. P. Hirshman and J. T. Hogan.
3P12. Beam-Driven Drift Instability in a Thermal Barrier Cell. V. A. Thomas and W. M. Nevins.
3P13. A Nonlocal Treatment of Drift Waves in Cylindrical Geometry. R. D. Ferraro, R. G. Littlejohn, H. Sanuki, and B. D. Fried.
3P14. Theory of R.F. Stabilization of Axisymmetric Tandem Mirrors. P. L. Similon, A. N. Kaufman, and D. D. Holm.
3P15. Effects of Trapped Hot Ions on High-Beta MHD Modes. J. S. Kim, M. S. Chu, and J. K. Lee.

3P16. Convection in Tandem Mirrors Caused by Temperature Inhomogeneity. T. Ohkawa.
3P17. Study of Generalized Toroidal Cusp Configurations. S. T. Ratliff, J. N. Leboeuf, and J. M. Dawson.
3P18. Relaxation of Tokamak Discharges. A. Khare, A. Bhattacharjee, and J. Manickam.
3P19. Destabilization of Micro-Tearing Modes by Cross-Field Transport. J. M. Finn and J. F. Drake.
3P20. A Perturbation Solution of the Fokker-Planck Equation for High Energy Ion Transport. B. D. Ganapol.
3P21. More About the Spectrum of the Resistive Alfven Wave. C. M. Ryu and R. C. Grimm.
3P22. Microwave Induced Neoclassical Transport in EBT Geometry. E. F. Jaeger, C. L. Hedrick, and D. B. Batchelor.
3P23. Confinement and Transport in Stellarators. O. Betancourt and P. Garabedian.
3P24. Magnetic Equilibrium and Single Particle Orbits in EBS. C. L. Hedrick and L. W. Owen.

3Q POSTER SESSION 10:30 - 12:15

3Q1. Renormalized Toroidal MHD Equilibria. T. Yamagishi.
3Q2. Monte Carlo Estimates of Transport Rates in EBT with Asymmetric Potential Profiles. J. S. Tolliver and C. L. Hedrick.
3Q3. Limiter Stabilization of External Kink Modes. L. C. Bernard and J. K. Lee.
3Q4. RF Drift Pumping of Thermal Barriers. Y-J. Chen, D. E. Baldwin, and J. A. Byers.
3Q5. Predictions of Divertor Regions in IMS and ATF-1. R. P. Doerner, D. T. Anderson, and J. L. Shohet.
3Q6. Self Consistent and Combined Effects of the Wave Breaking, of the Trapping Effect and of the Wave Damping in a Hot Magnetoplasma. B. Lembege and J. M. Dawson.
3Q7. Transport Calculation for a Field Reversed Configuration. D. E. Shumaker.
3Q8. Mercier Stability for Plasmas with Flow. E. Hameiri.
3Q9. The Importance of Electron Collisions for Ion Transport in Tokamaks. A. A. Ware.
3Q10. Thermal Effects on the Efficiency of Doppler-Shift Dominated Cyclotron Masers. A. T. Lin, W. W. Chang, and C. C. Lin.
3Q11. Cyclotron Maser Radiation from Mildly Relativistic Electron Distributions. P. L. Pritchett.
3Q12. Nonlinear Resistive MHD Calculations in a Poloidal Divertor Tokamak with the q = 1 Surface near the Separatrix. T. H. Osborne and S. C. Prager.
3Q13. On the Theory of Pairwise Coupling Embedded in More General Local Dispersion Relations. V. Fuchs, A. Bers, and L. Harten.
3Q14. Applications of Multi-region Fokker Planck Code to Modeling Tandem Mirrors. M. Baghaii and J. T. Woo.
3Q15. Magnetized RMJ Fokker-Planck Equation. M. H. A. Hassan.
3Q16. Numerical Simulation of Thermal Transport in the TEXT Tokamak. W. H. Miner, Jr., J. C. Wiley, and D. W. Ross.
3Q17. Incorporation of Time Dependent 2-d MHD Equilibrium Flux Surface Geometry in the TRANSP Transport Analysis Code. D. C. McCune, R. J. Goldston, and R. T. McCann.
3Q18. Current Ramp-up in Lower Hybrid Current Drive Experiments. R. W. Harvey, C. S. Liu, and P. L. Andrews.
3Q19. Large Wavelength Ballooning Modes in a Linear Multipole. D. A. Skinner.
3Q20. Are Major Disruptions Caused by Vacuum "Bubbles"? R. G. Kleva and J. F. Drake.
3Q21. Equilibrium Studies for Helical Axis Stellarators. T. C. Hender, J. Cantrell, B. A. Carreras, J. H. Harris, and J. A. Rome.
3Q22. A One-Dimensional Transport Code for Field-Reversed Configurations. E. J. Caramana, M. Y. Hsiao, and J. L. Schwarzmeier.
3Q23. ICRF Stabilization of Interchange Modes. J. B. McBride.
3Q24. A Numerical Method for Constant-Theta Tearing Modes. A. B. Hassam and B. D. Scott.

"THE INNER MAGNETOSPHERE OF JUPITER--THE IO PLASMA TORUS"

John W. Belcher

Massachusetts Institute of Technology
Department of Physics
Center for Space Research

SHERWOOD THEORY MEETING 1984

April 11 to 13

Stabilization of an Axisymmetric Tandem Mirror*

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We indicate how an axisymmetric tandem mirror plug, with a hot component plasma, can be stabilized by image currents of a conducting wall and finite Larmor radius. The stabilization mechanism has the virtue that it converts all MHD-like excitations to positive energy waves. As a result the stability is not limited by the Lee-Van Dam core beta threshold and the system is free of negative energy wave excitations that are destabilized when interacting with positive energy waves or dissipative mechanisms. The dispersion relation found connects conventional MHD waves with the precessional mode common in the Astron concept. If the plasma's diamagnetic current is large enough, the ℓ=1 mode can be stabilized by image currents induced in a nearby conducting wall. Higher ℓ numbers are stabilized by a finite beta FLR effect. Unlike conventional FLR stabilization, this stabilization does not produce negative energy waves. However, the stability condition is more difficult to fulfill and a stable plasma can contain only a few gyro-radii of the hot component plasma.

*Work supported by USDOE.

RAPIDLY CONVERGENT ALGORITHMS FOR 3-D EQUILIBRIA IN TANDEM MIRRORS AND STELLARATORS IN THE PARAXIAL APPROXIMATION*

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The relaxation methods of Chodura and Schluter(1) and refinements like Hirshmans'(2) method for finding stellarator equilibria take thousands of steps. Even with the simplifications of the paraxial limit, this is still so for tandem mirror calculations by H. Strauss(3) and L.D. Pearlstein et al.(4) The current balance algorithm converges in 10-20 steps.

In the tandem mirror, the method starts from the paraxial form of parallel and perpendicular pressure balance. Field lines start from the vacuum field positions adjusted for plasma diamagnetism and are then moved incompressibly by $dx/dt = \nabla U x z$, to the final equilibrium positions. The required flow U is formed by linearizing the local expression for the parallel current, $i_L = (J \cdot B)/B^2 = \underline{X} \cdot \nabla x \, \underline{X}'$, and equating it to the integral expression from $\nabla \cdot J = 0$, $J \times B = \nabla \cdot \underline{\underline{P}}$,

$$i_p = 1/\sigma \int_{-L}^{z} 2\kappa \, \overline{p}_\psi \, dz/B \text{ where } \sigma = 1 + (p_\perp - p_\parallel)/B^2, \; \overline{p} = (p_\perp + p_\parallel)/2,$$

and κ is the geodesic curvature. This gives

$$\nabla^2 (BU)'/B = (i_L - i_p) + [U, i_L] - B([x, BU[x, B'/B]] + x \rightarrow Y).$$

which is solved for $(BU)'$ on each plane z. The integration constant $\phi(\psi,\theta)$ is determined from the constraint that $\overline{i}_p = i_p(z = +L)$ vanishes in the vacuum, which yields a parabolic equation for ϕ as, $a\, \phi_{\theta\theta} + b_{\psi\phi} + c\phi_\theta + d\, \phi_\psi + e\phi = S$.

Most of the motion, $O(\beta)$, comes from the local current balance, and the constraint supplies an $O(\beta^2)$ piece. The coefficient 'a' is the flute stability integral and the method diverges as this limit is approached.

The extension to large-aspect ratio stellarators requires that the surface average parallel current be zero and that i_p be periodic. These two conditions determine ϕ and its surface average $\overline{\varphi}(\psi)$.

The algorithms for tandem mirrors and stellarators will be described. They are the finite β extensions of the method of Pearlstein(5) et al. and of the stellarator expansion.(6) Studies of several tandem configurations will be reported.

1. R. Chodura, A. Schluter, J Comp Phys. 41 (68-88) 1981.
2. S. Hirshman, Phys Fluids, 1983.
3. H. Strauss, Nuc. Fus. 1982.
4. L.D. Pearlstein, T.B. Kaiser, B. McNamara, Bull Am Phys Soc. P. 1185 28, 1983.
5. L.D. Pearlstein, T.B. Kaiser, W.A. Newcomb, Phys Fluids, 24 1326 (1981).
6. J.M. Greene, J.L. Johnson, Phys Fluids, 4, 875 (1961).

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Dissipative Trapped Particle Modes in Tandem Mirrors*

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We consider trapped particle modes in a tandem mirror. Past studies primarily considered the high mode number, collisionless limit when the configuration was strongly flute stable. In this work the analysis has been extended to (1) treat cells of arbitrary scale length, where flute stability is not necessarily strongly satisfied and (2) to include collisional and collisionless dissipation that can destabilize an otherwise stable system. To treat the problem of arbitrary scale lengths we model the system with each region treated as a square well and use a Lorentz collision operator. The model is most realistic if $|e\Phi/T_e << 1|$, where Φ is the variation in the equilibriuim potential between the anchor and center cells. We find that the perturbed potential in the plugs can be appreciable, and that the stability condition in the absence of dissipation is significantly more stringent than previous calculations. When the axial variations in the equilibrium potential are significant, a Lorentz operator does not adequitely describe the electron collisions. This limit is analyzed using an approximation in which the anchor length is assumed short compared to the central cell length and the system is assumed to be strongly flute stable. In addition to pitch-angle scattering, both energy diffusion and drag are included in the electron collision operator, and Landau damping is retained in the ion response. In this calculation the collisional problem can be solved in terms of the Pastukov loss rate from an electrostatic trap in most regimes of electron collisionality. If $\nu_{eff}/\omega_* < 1$ we find that if a collisionless analysis produced stability from positive (negative) charge uncovering, the resulting high frequency wave with $\omega \approx \omega_{*i}(\omega_{*e})$ is destabilized by ion (electron) collisional and collisionless dissipation and stabilized by electron (ion) dissipation, while the resulting low frequency wave is destabilized by electron (ion) dissipation and stabilized by ion (electron) dissipation. For $\nu_{eff}/\omega_{*e} > 1$, the only trapped particle wave has $\omega \approx \omega_{*e}$, and it is destabilized by electron collisions. In addition, there are flute-like modes which are closely related to modes described by a conventional MHD analysis.

* Work performed jointly under the Auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48; Institute for Fusion Studies, DE-FG05-80ET-53088; and University of California, Berkeley, DE-AT03-76ET-53059.

Boundary-Layer Transport in Tandem Mirrors with Axisymmetric Throttles*

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A tandem mirror machine with axisymmetric throttles is one, such as MFTF-B operating in the MARS mode, in which an axisymmetric mirror (mirror ratio R relative to the solenoid) separates the axisymmetric solenoid from the non-axisymmetric endplugs. Such machines have the property that a, the radial magnetic drift per bounce of an ion, is a discontinuous function of the velocity at the separatrix dividing ions confined to the solenoid and those passing into the end cells. Particles in a collisional boundary layer about the separatrix participate in a radial diffusion process which dominates over resonant banana transport at low collisionality and thus will be the most important ion transport mechanism in MFTF-B (if collisionless stochastic transport is prevented). Here, a drift-kinetic treatment is used to obtain particle and energy transport coefficients for this process. These transport coefficients scale as expected for a boundary-layer process, $D \sim a^2(\nu_c \nu_b / R)^{1/2}$, where ν_c and ν_b are the collision and bounce frequencies. Numerical examples are presented for MFTF-B parameters.

* Work performed under the Auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48

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Tandem Mirror Transport and Induced Azimuthal Variation of the Electrostatic Potential*

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By considering a simple tandem mirror model, we demonstrate the importance of retaining the induced azimuthal variation of the electrostatic potential. This variation of the potential arises from imposing quasineutrality in the presence of the ion magnetic drifts caused by the quadrupole field. The usual square well resonant-plateau diffusion coefficient D is importantly modified by the induced azimuthal variation of the potential whenever the electron diamagnetic drift frequency Ω_{*e} and the $E \times B$ precession Ω are nearly equal in magnitude but of opposite signs. The net charge due to the radial ion magnetic drift can then drive large azimuthal potential variations because it remains nearly stationary in the laboratory frame. This situation occurs because the net charge drives a potential response near a zero of the plasma dielectric. Our tandem model assumes that radial electron losses and ion axial losses are negligible. Unlike the simple situation in which D is insensitive to Ω_{*e}/Ω (magnetic drifts only), as many as three ambipolar roots for tandem operation arise. Jumping between roots is forbidden based on energetics and radial ion flux conservation. Since only one root exists when particle source profiles decrease with radius, it must be employed. This root does not permit inverted or hollow density profiles that are possible when azimuthal electric fields are ignored. Our results suggest that there may be benefits to employing noninverted source profiles. Recent experiments on pure electron plasmas[1] have also emphasized the dramatic effect of the plasma dielectric response on radial transport.

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*Work supported by U.S. Department of Energy Contract DE-AC03-76-53057.

[1] D. L. Eggleston, J. H. Malmberg, and T. M. O'Neil, Bul. Am. Phys. Soc. 28, 1047 (1983).

SHERWOOD THEORY MEETING 1984

April 11 to 13

Validity of Mixing Length Saturation Theory and Its Implication for Anomalous Thermal Transport in RFP*

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The simple mixing length theory $|\tilde{v}_r|_{rms} = \langle\gamma\lambda\rangle$ has yeilded qualitatively accurate results for the fluctuation saturation level of resistive interchange modes in RFP. However, certain ambiguities appear when mixing length arguments are applied to the problem of saturation of zero frequency (MHD-like) instabilities. For example since the mode width Δ is a function of growth rate γ, the meaning of estimates such as $\delta p/p \sim \Delta/L_p$ at saturation (γ=0) is rather unclear. In general, a more precise understanding of the spatial (mixing length) and temporal (correlation time) scales at saturation is required. Here we present a detailed renormalized theory of the resistive interchange mode using the simplest possible model, which is electrostatic, incompressible reduced MHD. Random convection of pressure by fluid turbulence appears as an anomalous pressure diffusivity. The same diffusivity also accounts for the process of vorticity transport (anomalous fluid viscosity). Balance of anomalous viscosity with the (linear) resistive line bending determines the amplitude dependent mixing length. The saturation of resistive interchange modes is unambiguously determined by requiring $\partial E^K/\partial t=0$, where E^K is the fluid kinetic energy. From this saturation condition, it then follows that the (nonlinear) mixing length equals the linear mode width, thus vindicating the simple theory. Possible exceptions to this rule and other applications will be discussed.

Using the results obtained above, pressure and magnetic fluctuations $\delta p/p \sim \Delta/L_p \sim S^{-1/3}$, $\delta B/B \sim \beta_p^{4/3} S^{-2/3}$ (Δ = mode width) result. It follows from consideration of magnetic field line diffusion that the anomalous electron thermal conductivity $\chi_E \simeq (1/4\pi)^{1/2}(\varepsilon/q)^3 \beta_p^{3/2} v_{Te} a/S$. Balance of thermal loss with ohmic heating indicates a constant $\beta \sim 10\%$ and hence $T_e \sim I_p^2/N \sim I_p$ (for $N \sim I_p$), in qualitative agreement with experiments. The similarity of thermal loss predictions for resistive interchange modes to those reported before for m=1 tearing modes indicates that turbulence within (tearing) and beyond (pressure driven) the field reversal point gives rise to comparable thermal transport. Hence, it appears plausible that RFP thermal transport is insensitive to small variations in θ and F. Effects of compressibility and electromagnetic fluctuations will be discussed.

*Work supported by USDOE.

Abstract for 1984 Annual Controlled Fusion Theory Conference

Survey of Theories of Turbulence and Anomalous Transport in Tokamaks

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The search for an explanation of the anomalous transport in tokamaks remains one of the most challenging problems in fusion plasma theory. The recent unexpected discoveries of operating regimes with improved energy confinement in Alcator C, ASDEX, DIII, PDX and ISX-B only serve to underscore the lack of understanding of transport in tokamaks. The anomalous transport has generally been attributed to microscopic plasma turbulence, but so far theoretical transport coefficients have not been very successful in predicting or interpreting the observed transport. As a result of the many measurements of the microturbulence in tokamaks, it has been recognized that a tokamak plasma is strongly turbulent so that models based on weakly-interacting normal modes are probably not sufficient to explain the transport.

In this poster, recent theoretical work on turbulence and transport in tokamaks will be surveyed. Some of the work on strong drift wave turbulence, stimulated in part by the experimental observations on tokamaks, will be reviewed. Also, stochastic magnetic field transport and MHD turbulence in tokamaks will be discussed, as well as recent experimental and theoretical work linking the observed microturbulence to anomalous transport.

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CURRENT-DRIVE BY FAST WAVES*

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The application of fast wave (or magnetosonic wave) with frequency near the lower hybrid frequency for plasma heating and steady-state current maintenance in tokamaks has been considered to have certain advantages as compared with the use of the slow wave, particularly at higher densities. In this paper, we study the penetration, absorption, and possible current-drive by means of fast waves.

For efficient coupling, the initial $N_{||}$ is required to be small. However, in the presence of random density fluctuations near the plasma boundary, one expects an enhancement in the refractive index before the energy in the fast wave has been transferred to the slow wave through mode conversion. For small change in $N_{||}$, mode conversion is expected to happen before the wave has penetrated too far. Basically, then, the problem becomes similar to that of the slow wave interacting with the plasma.[1] For large change in $N_{||}$, direct penetration to the interior is possible. In the latter case, absorption may occur through tail electrons (for $\omega \sim \omega_{LH}$); in that case, damping is stronger than fast wave damping at $\omega \sim \Omega_i$ on the thermal bulk. The condition on $N_{||}$, necessary for such absorption, is then found. This also determines the condition for efficient current-drive by fast waves.

In the presence of alpha particles (e.g., in a reactor device), however, the absorption of fast waves by such particles appears stronger than that by electrons. The implications of this fact on current-drive will be discussed.

[1]P.L. Andrews *et al.,* this conference.
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SHERWOOD THEORY MEETING 1984

April 11 to 13

FLUID DESCRIPTION OF MICROTEARING TURBULENCE IN A SHEARED SLAB

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A model set of fluid equations is employed to analytically study the effects of density and magnetic turbulence on the temperature gradient driven collisional microtearing mode[1] in the context of multiple helicity overlapping islands. For simplicity, Ohm's Law, Ampere's Law, and electron density conservation are used, while the electrostatic potential and density gradient are ignored. In this model, the source is the time dependent thermal force[2] and the main sink is ohmic dissipation. It appears that little or no nonlinear reduction of this (linear) source occurs. Hence, the a-priori application of mixing length arguments is unclear. Therefore, transfer of energy to small scales (ohmic dissipation) via incoherent and coherent mode coupling is a very likely saturation mechanism.

Renormalized spectral evolution equations are derived from the basic hydrodynamic equations. Effects include anomalous radial electron particle diffusion in the density equation and anomalous resistivity in Ohm's Law, part of which is related to a cascade of mean square flux to long scales. Also, inclusion of temperature fluctuations will be discussed. Preliminary results on transport and saturation levels related to tokamak edge turbulence will be presented.

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A THREE-DIMENSIONAL MODEL FOR RELAXATION PHENOMENA

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A problem of interest in RFP and CT plasmas is the dynamics of relaxation to a force-free state [1]. Recent experimental schemes for providing steady-state current and flux regeneration in both RFPs [2] and spheromaks [3] probably depend in part on the existence of these relaxation phenomena. In order to assess such schemes, solutions to these inherently three-dimensional problems must be found. Such motions occur on time scales long compared to Alfvén times, and hence present computational difficulties.

In this paper we present a computational model for the simulation of these processes. We assume that the plasma is continually driven away from a minimum energy state through the application of boundary conditions (i.e., either ac or dc applied voltages), and that the plasma relaxes to a force-free state through the action of perpendicular currents alone; the pressure is ignored. Fast time scales are eliminated by replacing the time derivative in the momentum equation with a phenomenological drag. (Viscosity may also be included, allowing the imposition of various boundary conditions on the flow.) With these assumptions, the combination of Ampère's law and Ohm's law yields an anisotopic diffusion equation for the vector potential that completely describes the response of the system to voltages driven at the boundaries. With the proper choice of gauge, a tractable computational model is obtained. This model is similar to one previously used to compute undriven three-dimensional force-free equilibria [4]; however, in our case a single-step algorithm results.

This model will be initially applied to F-θ current drive in the RFP. Applications to steady-state spheromaks may also be possible.

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INJECTION AND TRAPPING OF AN ION RING IN A COMPACT TORUS CONFIGURATION*

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An ongoing study at Cornell deals with the problem of merging an ion ring with a Compact Torus.[1] Energetic particles can heat, stabilize or maintain the flux of the configuration into which they are injected. The ring injected from a source[2] has an initial kinetic energy in the range 5-15% of the total energy. This axial energy must be reduced significantly by the time the ring approaches the CT for efficient trapping. One technique for achieving this objective is by propagating the ring in a low density background plasma in which it loses energy to the excitation of compressional Alfven disturbances. The reduction in kinetic energy ΔK is given by

$$\Delta K = -\frac{2\pi}{c}\int r\,dr\,dz\,\left\{\frac{Q^2 B_p^2}{2\rho_o c} + \frac{c}{\sigma}\int_o^t dt'\, j_b^2\right\},$$

where $Q = \int_o^t dt'\, j_b(\underline{x},t')$; j_b is ring current density, ρ_o is the plasma mass density and B_p is the poloidal field. The first term in the expression for ΔK represents the losses to wave generation and this dominates over the second term which arises directly out of resistive losses of the induced plasma currents. The wave generation term shows the importance of maximizing the ring current density. In order to achieve this during propagation the following conditions have to be observed: (1) the ring axial pressure is balanced by its self-magnetic field to maintain axial equilibrium and prevent spreading, (2) the self-magnetic field gradient must exceed the gradient in the external field to prevent ring ion detrapping, and (3) the ring moves coherently at less than the local Alfven velocity. We are using the computer hybrid particle code CIDER to make an assessment of these three criteria and to show the final trapping process of ring ions in the Compact Torus.

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Helical Axis Stellarator Equilibria*

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An asymptotic ordering is developed to model equilibria of systems with a helical magnetic axis, such as the Asperator at Sendai and the Heliac proposed at Princeton. The ordering, based on the stellarator approximation,[1] has $\gamma^2 \sim \delta^2 \sim \varepsilon \sim \beta << 1$, where $\gamma \equiv ha$ measures the wavelength of the dominant $\ell = 1$ helical field with respect to the plasma radius, δ is the ratio of the magnitude of this field to the toroidal one, ε is the inverse aspect ratio, and β is the pressure. A multiple scale analysis is invoked to differentiate between long and short toroidal length variations. An analytic expression for the lowest order vacuum field flux function Ψ^o has been calculated for the Asperator.[2] In the current work, the effects of plasma pressure are incorporated. The usual averaging procedure leads to an equilibrium formulation that is two dimensional in the characteristic coordinates C_1 and C_2,

$$\Psi^o = C_1^2 + C_2^2 + \frac{5\varepsilon}{\gamma^2} C_1 + \frac{4}{\gamma\delta^2} A^\sigma ,$$

$$\frac{\partial^2 A^\sigma}{\partial C_1^2} + \frac{\partial^2 A^\sigma}{\partial C_2^2} = \frac{2p'(\Psi^{(0)})\varepsilon}{\gamma} C_1 ,$$

$$C_1 \equiv x - \frac{\delta}{\gamma}\cos t \quad , \quad C_2 \equiv y - \frac{\delta}{\gamma}\sin t \quad ,$$

where (x,y,t) form a local Cartesian coordinate system. Solutions for simple pressure profiles are presented. The analysis for Heliac leads to a similar but more complicated set of equations.

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†On loan from Westinghouse R&D Center, Pittsburgh, PA 15235.

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CHARACTERIZATION OF STOCHASTIC FIELD LINES IN RFP PLASMAS

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Energy confinement in Reversed-Field Pinch (RFP) plasmas is of both theoretical and experimental interest. There is a discrepancy between experimentally measured confinement times (in ZT-40M), and those determined by classical perpendicular ion thermal conduction. Various models have been proposed to account for this difference, and also to predict the confinement scaling. Those based on completely stochastic, or tangled, discharges [1] have required field line lengths of many kilometers to account for the observed values, and predict poor confinement. Recent three-dimensional MHD computer simulations [2,3] have shown that during its dynamical evolution, the pinch may become almost completely stochastic, depending on the value of the pinch parameter θ. However, in the asymptotic time regime, good flux surfaces are found to exist in the outer 10-30 percent of the minor radius. To investigate the consequences of such a configuration on the energy confinement, it is necessary to estimate stochastic radial transport coefficients due to magnetic field lines that wander ergodically in space.

In this paper, we have used the field line tracing code TUBE, and taken an intersection of the magnetic field lines with the r-z plane for a given value of θ at various times. The resulting punctures are a qualitative indicator of the existence of good flux surfaces or stochastic regions. We have used standard statistical methods to quantify these stochastic regions. An assessment on the impact of energy confinement is made.

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Nonlinear Fluctuations of an Ideal Two Fluid Model: Stochastic Transition vs Transport?

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It is well known that Hamiltonian systems may have stochastic orbits without being ergodic. Numerical studies of such systems with many degrees of freedom have been reported in the solid state physics literature[1]. For low excitation energies one finds a positive Lyapunov exponent, but no trend toward energy equipartition.

An ideal two fluid MHD model has been constructed with the following properties: the energy is a positive quadratic functional of the fields; there is a Liouville theorem; the light fluid (the electrons) has three dimensional guiding center motion. Does there exist a parameter regime in which field lines are stochastic but there is no sharing of energy amongst the normal modes? Would the existence of such a regime imply diffusion of test particles but not of plasma energy?

It is hoped that preliminary numerical simulations will give some indication of the answer to the first question.

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Low-n Toroidal Shear Alfvén Waves*

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It is well known that in an axisymmetric plasma the toroidicity can cause coupling of neighboring poloidal harmonics and break up the shear Alfvén continuous spectrum. We have found discrete toroidal shear Alfvén waves inside the continuum gaps by using the high-n ballooning formalism. In this paper, we show by both analytical and numerical computations that low-n toroidal shear Alfvén waves may also exist inside the continuum gaps. Numerically, we first determine the continuous spectrum for all flux surfaces and then use the PEST code to obtain the discrete toroidal shear Alfvén wave inside the continuum gaps. For a typical tokamak equilibrium, the n = 1 mode is dominated by m = 1 and m = 2 components which are localized near the q = 1.5 surface. An analysis restricted to two neighboring poloidal harmonic results in a fourth order equation, which is then solved and confirms the numerical solutions. Potential applications of the toroidal shear Alfvén eigenmode on plasma heating and instabilities will be addressed.

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NONLINEAR EVOLUTION OF DRIFT TEARING MODES*

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The nonlinear evolution of drift-tearing modes is investigated. We show that diamagnetic propagation of these modes ceases at island widths of order 1 cm for representative tokamak parameters. Propagation of smaller islands results from the connection of differing regions of electron pressure by the associated magnetic perturbations. This propagation is dramatically slowed for larger widths as the local density profile is flattened by sound waves. The critical density flattening width is given by the condition $k_{\parallel}(w)c_s \sim \omega_*$, where ω_* is the drift frequency, c_s is the sound speed, and $k_{\parallel}(w)$ is the parallel wavenumber at the edge of the island. This has been confirmed by a nonlinear initial-value code developed to study drift-tearing modes. Rotating m = 2 islands of larger width are generally observed in many tokamak discharges, implying that this rotation must be due to radial electric fields. In this sense, then, observations of rotating magnetic islands are supplying information on the local electrostatic potential gradient in these discharges.

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NUMERICAL SIMULATION OF ELECTROMAGNETIC TRAPPED ELECTRON TURBULENCE IN TOKAMAKS*

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Nonlinear equations for an isothermal three-fluid model consisting of trapped electrons, passing electrons, and ions are written for a low collisionality tokamak plasma. A vorticity equation, continuity equations for the electrons and trapped electrons, a generalized Ohm's law for the passing electrons, and ion parallel momentum balance are used for the time evolution of the perturbed electrostatic potential, electron and trapped electron densities, vector potential, and parallel ion motion ($\tilde{\phi}$, $\tilde{n}$, $\tilde{n}^t$, $\tilde{A}_{||}$, $\tilde{u}_{||}$):

$$(\tilde{d}/dt)(k_\perp^2 \phi_k) = i\omega_g N_k (1+\tau^{-1}) + \omega_* \tau^{-1}(k_\perp^2 \phi_k) - \tilde{\nabla}_{||}(k_\perp^2 A_k)$$

$$(\tilde{d}/dt)N_k = -i(\omega_* - \omega_g)\phi_k - i\omega_g N_k + \tilde{\nabla}_{||}(k_\perp^2 A_k) - \tilde{\nabla}_{||} U_k$$

$$(\tilde{d}/dt)N_k^t = -i(\omega_* - \omega_g)\sqrt{\epsilon}\,\phi_k - i\omega_g N_k^t - (\nu/\epsilon)[N_k^t - \sqrt{\epsilon}\, N_k^u/(1-\sqrt{\epsilon})]$$

$$(\partial/\partial t)A_k = -i\omega_* A_k + (2/\beta_e)\tilde{\nabla}_{||}[N_k^u/(1-\sqrt{\epsilon}) - \phi_k]$$

$$(\tilde{d}/dt)U_k = -\tilde{\nabla}_{||} N_k^u/(1-\sqrt{\epsilon}) - \tau^{-1}\tilde{\nabla}_{||} N_k + (1+\tau^{-1}) i\omega_*(\beta_e/2)A_k - \mu_{||} k_{||}^2 U_k,$$

where $\phi \equiv (e\tilde{\phi}/T_e)/(\rho_s/L_n)$, $N \equiv (\tilde{n}/n_o)/(\rho_s/L_n)$, $N^u \equiv N - N^t$, $A \equiv (e\tilde{A}_{||}/T_e)(c_s/c)$ $(2/\beta_e)/(\rho_s/L_n)$, $U \equiv (\tilde{u}_{||}/c_s)/(\rho_s/L_n)$, $k_{||} \equiv k_{||}L_n$, $k_\perp \equiv k_\perp \rho_s$, $t \equiv t\omega_s$, $\nu \equiv \nu_{ei}/\omega_s$, $\epsilon \equiv r/R$, $\omega_s = c_s/L_n$, and $\tau^{-1} \equiv T_i/T_e$. The trapped electron fluid carries no current and does not respond to parallel electric field perturbations. It is collisionally detrapped and re-trapped. Finite Larmor radius for the ions and curvature drifts for all species are included. The nonlinear terms arise only from the $\tilde{E}\times B_0$ convection $[\tilde{d}/dt = \partial/\partial t + \tilde{v}_{E\perp}\cdot\nabla_\perp]$ and magnetic flutter $[\tilde{\nabla}_{||} = \nabla_{||} + \tilde{B}_\perp/B_0\cdot\nabla_\perp]$. Simplified two dimensional $(\vec{k}_\perp)$ mode coupling calculations with a fixed average parallel wave number $(k_{||} = 1/Rq)$ and curvature drift $[\omega_g = (L_n/R)\omega_*]$ are performed. Stationary, homogeneous turbulent states driven by the trapped electron drift-ballooning modes are obtained for values of $\beta < \beta_{crit} = 2\,L_n/Rq^2$ where the ideal MHD ballooning modes onset. The $\tilde{E}\times B_0$ transport is calculated. The behavior is summarized by comparison to simple scaling laws [e.g., $\tilde{n}/n_0 \sim 1/k_\perp L_n$, $\tilde{B}_\perp/B_0 \sim \beta(q/2)\tilde{n}/n_0$]. The results are anologous to those of a similar study of a high collisionality tokamak plasma[1] provided we identify the $\beta = 0$ adiabaticity parameter as $\alpha_0 = \nu_{ei}/\epsilon\omega_s$ for the trapped electron plasma in place of $\alpha = k_{||}^2 v_{eth}^2/2\,\nu_{ei}\omega_s$ for the collisional plasma.

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SIMULATION OF THE EVOLUTION OF A SPHEROMAK*

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We consider a zero-β spheromak contained in a rectangular region having perfectly conducting boundaries in its minimum energy state, and we calculate its evolution. Our results may be summarized as follows. Since this state is a stable equilibrium, the initial evolution of the plasma is caused by diffusion. We simulate this using a transport code. We find that q at the magnetic axis drops and q(r) becomes flat. When q on axis drops below .5, the spheromak becomes unstable to an n=2 kink. The plasma is then modeled dynamically; the kink displacement saturates and eventually reverses when a reconnection occurs. A new magnetic axis begins to form as the plasma relaxes toward a minimum energy state.

We first present the evolution during the diffusion phase. This evolution is calculated with the "1-1/2D" transport code MINERVA. In such a code the plasma inertia is neglected and the plasma evolves through a sequence of quasi-equilibria. Two-dimensional equilibria are calculated, all thermodynamic variables are assumed to be constant on a flux surface, and the diffusion (1D) of these variables across the flux surfaces is computed. The resistivity profile in this calculation is $\eta = \eta_0(1+\varepsilon-\psi)$, when $\psi = 0$ at the boundary and $\psi = 1$ at the magnetic axis. η_0 and ε are chosen so that the temperature implied if η were classical resistivity with $z_{eff} = 1$ is 4.5 eV at the boundary and 23 eV at the magnetic axis. A resistivity profile is required in this calculation because if η were constant in space, the spheromak fields would simply decay self-similarly. In the initial state the q(r) profile at the z midplane increases monotonically from 0.4 at the boundary to 0.6 at the magnetic axis. Diffusion causes the q(r) profile to become flat over the 30-40% of the plasma closest to the magnetic axis. In this region the shear is small.

Two-Dimensional linear stability codes are used to check the stability of the equilibria during the diffusion phase. Both an ideal and a resistive code are used. The equilibria described above are found to become unstable when q on the magnetic axis drops below .5. Both codes show that the n = 2 mode is unstable and that the growth time is less than the diffusion time. The growth times calculated by both codes agree to within a factor of two, so that the mode is a resistively modified ideal mode.

We next consider the dynamical relaxation of this unstable equilibrium by using the 3D resistive MHD code TEMCO. This code is initialized with the unstable equilibrium and the n = 2 unstable perturbation. No other modes are included. The resistivity is uniform and we consider here the simulation having $S = \tau_R/\tau_A = 10^4$. The 3D magnetic field is input to the TUBE code, which outputs puncture plots in a given poloidal plane. We find that the unstable perturbation initially grows and the plasma moves nearer the boundary. Eventually this displacement reverses itself and the plasma moves in the opposite direction. An additional magnetic axis begins to form, and the plasma then appears to approach a stable equilibrium, as the remaining flux in the old island associated with the first magnetic axis resistively dissipates.

A result of this evolution is that the plasma is closer to the minimum energy state than at the beginning of the relaxation.

In conclusion, these calculations demonstrate that superimposed on the overall resistive decay of the magnetic configuration is an n = 2 oscillation, with the resistivity profile driving the spheromak away from the minimum energy state to an unstable equilibrium, and the consequent dynamical relaxation driving it back toward a stable equilibrium. The extent to which this agrees with experimental observations of decaying spheromaks is considered.

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Electron Heating by Waves at Ion Frequencies

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ABSTRACT

In the EBT device and in some mirrors a hot thin electron ring is present. When ICRH is applied to the system, the hot ring is exposed to waves at ion frequencies. The interaction between the wave and the electron ring is studied by taking a slab geometry model for the hot electrons with a constant magnetic field. The hot electrons are in a ring a few Larmor radius thick and thus are presented by a non-Maxwellian, anisotropic distribution function. The incident wave has a wave vector mainly perpendicular to the magnetic field with a small parallel component, so that both parallel streaming and finite Larmor radius effects are present. It is shown that several percents of the energy flux may be absorbed by the electrons in a single pass of the waves through the ring. This process may be responsible for the heating of the electron ring which is observed in EBT. Numerical results are presented for a wide range of parameters. For special cases, typical to the situation in current experiments, Born approximation and small FLR expansions yield analytic formula for the absorption which agrees with the numerical results of the full equation.

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SIMULATION OF IMPURITY TRANSPORT IN THE ISX-B TOKAMAK WITH DIRECTED NEUTRAL BEAM HEATING*

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Experiments on beam-heated ISX-B and PLT plasmas indicate that counterinjection leads to enhanced accumulation of impurities and coinjection leads to reduced accumulation of impurities relative to ohmic heated plasmas. Stacey and Sigmar have recently included the effects of the strong toroidal rotation induced by directed neutral beam heating in a self-consistent theory for particle flows within the flux surfaces, the radial electric field, and the radial particle transport in a tokamak plasma with directed neutral beam injection in both the collisional regime and in a mixed regime in which the main plasma ions are in the plateau regime while the impurities remain in the collisional regime.

We have implemented the collisional regime theory in our basic impurity transport simulation code, IMPTAR, and present here simulation results for both coinjected and counterinjected plasmas. These results are qualitatively similar to results reported previously for simulations in which the rotation effects and all other momentum exchange effects were treated separately. That is, for plasmas with ion density and temperature gradients comparable to those observed in ISX-B: (1) enhanced impurity accumulation is observed in simulations of counterinjected plasmas and (2) impurities are initially driven out of the plasma during coinjection, but after large rotation speeds are reached, there is a tendency for the impurities to be driven back into the plasma. Although some attempt was made to account for the low collisionality of the plasma ions in these simulations, implementation of the mixed-regime theory is required to adequately represent the actual plasma conditions.

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STOCHASTIC MOTION OF MIRROR-CONFINED ELECTRONS BY A FREQUENCY-MODULATED WAVE *

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The electrostatic potential in the end-plugs of a tandem mirror plasma is given by the Boltzmann relation for a Maxwellian plasma: $\Delta\phi = T_c \ln(n_p/n_c)$, where $\Delta\phi$ is the potential difference between the end-plug and the central-cell, T_c is the central-cell electron temperature and n_p, n_c are the electron densities in the plug and the central cell, respectively. In order to make the dependence of $\Delta\phi$ on n_p/n_c more favorable, the distribution function for the electrons, f_e, in the end-plugs has to be significantly modified away from a Maxwellian. One technique for doing this would be by the use of externally launched RF waves that modify f_e along the magnetic field. In contrast to the use of ECR power, which is commonly the means for generating potentials in tandem mirrors, we propose the use of a frequency modulated low-frequency electrostatic wave (ESW) resonant with the electron bounce motion. To study the effect of RF on electron trajectories and, consequently, the effect on f_e, we consider a one-dimensional model. This model studies the motion along the magnetic field of electrons that are confined by a magnetic well and an electrostatic potential. The equation of motion is:

$$m\frac{d^2z}{dt^2} = -\frac{\partial\psi(z)}{\partial z} - eE_z\cos(kz - \omega t - \delta\sin\omega_m t)$$

where $\psi(z) = \mu B(z) + e\phi(z) \;\alpha\; \sin(k_0 z)$ is the static confining potential, μ (m, e) is the electron magnetic moment (mass, charge), $k(\omega)$ is the wavenumber (frequency) of the ESW of strength E_z and, δ (ω_m) is the modulational index (frequency). We find that by an appropriate frequency modulation the ESW induces significant stochastic behavior in the electrons whose velocities are very different from the phase-velocity of the wave. For TARA parameters, the electron distribution function in the velocity region $0 \le |v_z| \le 2v_{te}$, where v_z is the velocity of the electrons and v_{te} is their thermal velocity ($T_e = 800$ eV), can be flattened on a time-scale that is small compared to the electron-electron collisional time. This requires an ESW of strength $E_z = 0.2$ V/cm whose frequency is $\omega \approx 4.2 \times 10^7$ sec^{-1} and whose k can be freely chosen as long as $\omega/k \ge 2v_{te}$. The appropriate choice of δ is around 10 and of $\omega_m = 0.01\,\omega$. This corresponds to a frequency modulation of 10% around ω which can be easily achieved experimentally.

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AN OBSTACLE TO PREDICTABILITY*

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A typical dissipative dynamical system may possess more than one time-asymptotic final state (or attractor). It will be demonstrated that in this case, very accurate specification of initial states may be required for reliable prediction of final states. Specifically, for initial conditions selected with error ε, we define the fraction f of phase space consisting of initial conditions whose final states cannot be predicted with certainty. We show that in general this fraction f scales as[1]

$$f \sim \varepsilon^{\alpha} , \qquad 0 < \alpha \leqslant 1 ,$$

where the exponent α is related to the fractal dimension of the boundary separating the basins of attraction. Furthermore, it is shown that $\alpha \ll 1$ holds in a variety of standard dynamical systems. Thus, we expect that in a typical system, a substantial reduction of initial condition error will yield only a relatively slight increase in one's ability to predict the result of an experiment on that system.

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Simulation of Mode Induced Beam Loss in Tokamaks*

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A Hamiltonian guiding center drift orbit formalism[1] is used to investigate the interaction of high energy trapped particles and the internal kink mode. This mode is destabilized by the trapped particles at a critical hot particle beta. It has a growth rate near the ideal magnetohydrodynamic value and a frequency near the trapped particle precession frequency.[2] Such a mode will rapidly eject the trapped particles, leading to stabilization.[3] Constant replacement of the trapped particles through neutral beam injection then leads to a coupled system which exhibits periodic bursts of high frequency magnetohydrodynamic activity and high energy particle loss. Detailed theoretical comparisons have been made with the fishbone instability observed on PDX,[4] including MHD activity, particle losses, particle energy distribution and neutron emissivity. Results are in essential agreement with experiment.

*This work supported by U.S. DoE Contract No. DE-AC02-76-CHO-3073.

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ENHANCED NEOCLASSICAL DIFFUSION OF NONRESONANT PARTICLES IN A BUMPY TORUS

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ABSTRACT

Significantly enhanced neoclassical diffusion is found for the hot nonresonant species in an EBT device by considering the detailed pitch-angle scattering for the transition and passing particles. Due to the presence of transition particles (trapped-passing boundary), the drift kinetic equation has more pitch-angle structure in the vertical drift term than has previously been considered. Using a bounce-averaged, pitch-angle-scattering collision operator, this equation is solved numerically and evidence of a plateau regime is sought. Initial calculations using a collision operator which was not bounce averaged agree with Kovrizhnykh[1] in the collisional regime but yield diffusion coefficients as much as four times larger than Kovrizhnykh in the collisionless regime.

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1P20

Resistive Ballooning in Toroidal RFP's*

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Various toroidal RFP equilibria stable to ideal Mercier modes are subjected to resistive ballooning analysis. The stability properties of these configurations are thus investigated as a function of quantities that are experimentally measurable (viz. F and θ values). Some density fluctuation phenomena in RFP's can be attributed to resistive ballooning.

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Onset of Stochasticity and the Diffusion Approximation in Drift Waves‡

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In contrast to a longitudinal plasma wave, a drift wave acts over the entire single particle phase space. This feature precludes a simple use of the techniques presently available for predicting the onset of chaos in Hamiltonian systems. In order to be relevant to experimental situations, a criterion of stochasticity must be able to handle simultaneously a broad wave-number and a broad frequency spectrum. This paper reports the first steps toward the derivation of such a criterion and examines the validity of the diffusion approximation and the issue of long time correlations. The dynamics of test particles in the field of several linear drift modes is investigated in a slab geometry with periodicity along the slab. For two modes a generalized overlap criterion is derived. For a wave spectrum with a broad frequency spectrum, a simple area preserving map is derived.

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Asymptotic Analysis of rf-heated Collisional Plasma

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The interaction of a dc electric field with a plasma can be described in velocity space by balancing a Fokker-Planck collision operator with an electric acceleration term. Even if the plasma temperature is, by external means, kept constant, no steady state can result, because runaway electrons are created. An analogous problem is the interaction of rf waves with a plasma, and of particular importance is when high-power waves, such as lower-hybrid waves, are resonant with the tail of the electron distribution, resulting in plasma heating and current generation. Numerical studies have found a steady state,[1] but have not proved its existence. Rather, the numerical studies assume a priori the existence of such a state in the form of boundary conditions on the necessarily finite integration domain.

In this paper, we prove via an asymptotic analysis that a steady state does exist even for intense rf waves resonant with an infinite slab of velocity space, such as occurs with lower-hybrid current-drive and heating. Apart from academic interest in the asymptotic behavior, such a proof is useful in that it justifies the numerical solutions, indicating where the imposition of finite boundary conditions is valid. The method of calculating the asymptotic state can also be used to obtain an approximate analytic expression for the electron distribution function over all of velocity space. Comparing the analytic expression to numerical solutions shows that the analytic approximaton is quite good. Such an expression can be useful when a large parameter space must be surveyed, for example, to provide a best fit to experimental data.[2]

*This work is supported by U.S. DoE Contract No. De-AC02-76-CHO-3073.

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AN INCOMPRESSIBLE, PSEUDOSPECTRAL COMPUTATIONAL MODEL FOR THE REVERSED-FIELD PINCH

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Recent three-dimensional, compressible MHD simulations have yielded insights into the dynamical evolution of the Reversed-Field Pinch [1]. However, these calculations require considerable computer time due to the inclusion of fast magneto-acoustic waves in the model. The role of these modes in critical RFP dynamics is unclear.

We have developed a three-dimensional incompressible MHD code that eliminates the fast time scale. The implementation of the model differs from others [2] in that the pseudospectral algorithm [3] is employed. This has been found to be an efficient method of calculating the evolution of the hundreds of modes that may be required in RFP simulations [4]. The incompressible algorithm results in an increase in computation speed of a factor of twenty as compared to the compressible code [4].

Comparisons between conpressible and incompressible simulations of RFP dynamics are presented and discussed.

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CURRENT GENERATION IN STELLARATORS*

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The "ideal" Stellarator ($\langle \underline{j} \cdot \underline{B} \rangle = 0$ on each flux surface) requires special pressure and rotational transform profiles, and these profiles are not necessarily consistent with diffusion constraints. We have studied the generation of currents (in initially current free stellarators) which arise from:

- finite pressure due to external heating
- classical "bootstrap" effect, related to toroidal/nonaxisymmetric geometry
- direct external current sources (e.g., LH or NB).

We have thus extended the analytic results of Pustovitov.[1]

The NYU 3D transport equilibrium code[2] (3DETC) has been used for these studies, with the following modifications.

- the one-fluid transport model incorporates ripple thermal diffusivity
- model profiles have been adopted for external heating (centrally peaked) and recycling/radiation loss (increasing toward the edge)
- an external current source has been added.

While the transport model is relatively simple (1-fluid, model profiles) it fulfills the requirements of the "method of given pressure" proposed by Shafranov and co-workers,[3] in which the evolution of rotational transform is studied with model assumptions about the co-evolving particle and energy balance. In addition, it provides a self-consistent 3D geometry. The transform evolution equation is

$$\left.\frac{\partial}{\partial t}\right|_{\chi} \nu = \frac{\partial}{\partial \chi}\left\{\eta_{\parallel}\left[\Delta\left(\frac{\partial \chi}{\partial V}\right)^2 \frac{\partial \nu}{\partial \chi} + A/(\partial \chi/\partial V) - \langle J^s \cdot B \rangle\right]\right\} .$$

A is a classical version of the bootstrap current, χ is toroidal flux, and J^s is the external current source.

We find that significant evolution of the rotational transform occurs on the skin time, stimulated by each of the mechanisms mentioned above. Configurations based on the ATF torsatron have been specifically chosen for study.

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ELECTRON TRANSPORT OF A QUIESCENT PLASMA WITH A FINITE INHOMOGENEITY*

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The previously derived general expression of transverse diffusion coefficient[1] has been investigated for electrons in a plasma with a finite inhomogeneity ignoring the effects of turbulences. For the sake of simplicity, the longitudinal dielectric function of a local aproximation has been adapted omitting the contribution from poles.

The anomalous effects of magnetic field on electron-ion collisions, previously found as an anomalous pitch angle scattering,[2] again appears in the present problem and causes an anomalous electron diffusion. The basic physics is the following: electrons with parallel velocities of the order of magnitude of the ion thermal velocity interact with ions much more strongly in a magnetized plasma than in an unmagnetized plasma, even when the electrons have large perpendicular velocities.

This effect is important at the transition layer between a trapped and an untrapped distribution and also at near turning points of mirror or banana trapping, especially in a case of sloshing distribution. It offers an additional mechanism of an anomalous electron diffusion of tokamaks and one plausible mechanism of the density reduction during ECRH experiments in tokamaks.

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Higher Order Mode Conversion Problems*

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There are several important problems in mode conversion theory which require differential equations of higher order than four. One simple example of this is the differential equation which relates to the third harmonic problem.

$$y^{vi} + (1-\epsilon)y^{iv} - \lambda^2 z y'' - (\lambda^2 z + \gamma)y = 0$$

In this special case, the coefficient of the fourth derivative term is constant, so the sixth order term could be discarded and one would obtain nearly the same tunneling coefficient. The behavior of the electrostatic Bernstein mode would be improperly described, however, and the energy conserving model would not admit the deletion of the highest order term. In several other cases, which are more interesting in the sense that the fourth derivative term *does* vanish at some finite distance from the first mode conversion layer, the higher order equation is mandatory since it describes a second mode conversion near the first mode conversion layer. This type of problem can be represented by an equation of the form

$$y^{vi} + (\sigma - \delta\lambda^2 z)y^{iv} + \lambda^2 z y'' + (\lambda^2 z + \gamma)y = 0$$

where δ is frequently small, meaning the second mode conversion is well removed from the first. A particularly interesting case is the two-ion hybrid with minority hydrogen in deuterium when the effects of rotational transform are included as a local inclination of the static magnetic field so that the gradient of B is no longer perpendicular to B. The fourth order equations describing this case fail when the rotational transform is too large or the minority fraction is too large compared to the majority β. It is shown that the sixth order equation above can resolve the difficulties of the fourth order system, and that even though the mode conversion process is greatly changed(the propagating slow wave changes sides), the tunneling of the fast wave is essentially unaffected. It is also shown that several other minority concentration hybrid resonances involve a second mode conversion and may need to be described by a sixth order system. Whether an intrinsically higher order system can be successfully reduced to a lower order system is shown to be related to the distance between the mode conversion turning points. In general, if the second mode conversion point is in the asymptotic regime of the first mode conversion, then the problem is separable and may be successfully reduced to a lower order problem. If the second conversion is in the near or inner region of the first conversion, then the higher order system is essential to demonstrate the features of the conversion process. A final example is the very high harmonic case of a lower hybrid wave as it crosses ion cyclotron harmonics. This problem is formidable because the dispersion relation itself has a great many terms if the Bessel expansion is used since the finite Larmor orbit parameter $\lambda = \frac{1}{2}k_\perp^2 \rho_L^2$ is not small but large. An approximate electrostatic dispersion relation relevant in the lower hybrid parameter range has been found which is based on both the argument and the order of the Bessel functions being large. If the cyclotron harmonic layers are well spaced(the width of the absorption layer much smaller than the distance between layers), a simple analytic expression has been found which can be represented by a mode conversion equation. In this problem, rotational transform plays a nontrivial role and can lead either to a fourth or sixth order equation. Preliminary results will be presented.

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THE EFFECT OF HALL TERMS ON RESISTIVE g-MODES IN A REVERSED FIELD PINCH*

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Resisitive interchange modes in a cylindrical reversed field pinch are modeled using the linear, compressible, finite-beta initial value code ODRIC. The effects of isotropic viscosity, isotropic thermal conductivity and the Hall current are included in the code model. An equilibrium of Robinson[1] known to be stable to tearing modes is used. Axisymmetric (m = 0) and nonaxisymmetric (m = 1) modes are examined. In the case where the temperature perturbation is set to zero, the "odd" mode is dominant and is gradually stabilized as the Hall parameter $\gamma_H = (\omega_{ci}\tau_A)^{-1}$ is increased. Including the equation for the perturbed temperature, in the absence of Hall terms the odd mode is still dominant. Inclusion of the Hall terms tends to stabilize this mode. However, if the thermal conductivity is sufficiently small there is a critical value of the Hall parameter, γ_{HC}, above which the "even" mode is dominant; as γ_H increases beyond γ_{HC} its growth rate increases and may even exceed that of the odd mode at $\gamma_H = 0$.

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TRANSPORT ASSOCIATED WITH THE COLLISIONLESS DETRAPPING/RETRAPPING OF ORBITS IN A NONAXISYMMETRIC TORUS II*

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In a previous paper,[1] we discussed heuristically the transport scaling associated with the collisionless detrapping/retrapping orbits in a nonaxisymmetric torus. It is found that the transport scaling depends on the retrapping possibility of the toroidally trapped particles in a time scale of the order of ω_E^{-1} where ω_E is the $\vec{E} \times \vec{B}$ poloidal drift frequency. (Here we adopt the strong electric field ordering, i.e., $\omega_E > \omega_{\nabla B}$, the ∇B drift frequency.) Now we develop a kinetic method to calculate the transport coefficients in a stellarator with an even retrapping probability distribution in the pitch angle space. This method is a generalization of that developed in Ref. 2. The solution we obtain is continuous in both pitch angle and configuration space. It is found that if the probability distribution is localized around the trapping/retrapping boundary, the Kovrizhnykh scaling is obtained. On the other hand, if it is a uniform distribution, the Galeev and Sagdeev scaling prevails. Our approach can treat an arbitrary probability distribution; therefore, it represents a generalization of those two scalings. It is also found that the Galeev and Sagdeev scaling is strictly valid only in the limit of $\epsilon_h \gg \epsilon_t$. In case of $\epsilon_h \sim \epsilon_t$ and order of unity, correction is required. With slight modifications this method is also applicable to a rippled tokamak.

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ATOMIC PROCESSES FOR DIAGNOSING TOKAMAK PLASMAS*

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Major atomic processes (ionization, recombination, excitation and charge-exchange) will be discussed for the central and peripheral regions of tokamak plasmas. Effect of ion transport on calculations of ionization equilibrium will be presented. Application of spectroscopic techniques in the X-ray, EUV, UV and visible range of the spectra as a means of monitoring atomic processes and their effect on plasma parameters will be presented. We will also discuss the application of atomic processes for the identification of different problems occuring in tokamak plasmas. For example, the dependence of ion transport on central and peripheral plasma conditions can be studied from the spectroscopic observation of plasma oscillations and fluctuations. Investigation of impurity radiation on the central and peripheral temperatures behavior during ICRF heating. Furthermore, we will discuss application of spectroscopic techniques to study the correlation between location of ICRF heating layer and the ion temperature profile.

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Free Boundary Stellarator Expansion MHD Equilibrium and Stability Calculations*

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We study free boundary MHD equilibrium and stability of stellarators using the stellarator expansion[1] to reduce the equilibrium calculation to a two-dimensional one. Fixed boundary equilibria calculated using this model have been demonstrated to be in good agreement with three-dimensional equilibrium calculations.[2] Stellarator expansion Mercier and low n stability calculations have also been performed on a wide range of fixed boundary equilibria.

To address the free boundary stability problem we use a version of the PEST Code modified to include stellarator expansion terms.[3] Detailed comparisons between the results of the fixed boundary and free boundary calculations will be presented. In particular, using the fixed boundary approach, it has been shown that vertical field shaping is important for accessing high beta, net-current-free, stable configurations. It is, therefore, crucial to study the effect of vertical field shaping as a path to high beta using a free boundary equilibrium and stability model. Specific applications to the ATF device will be presented.

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.
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EFFICIENT MAGNETIC ANALYSIS OF NONCIRCULAR TOKAMAKS*

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For optimization of plasma betas in noncircular tokamaks, it is essential to have an efficient method that can rapidly and accurately determine the plasma boundary shapes and beta values directly from external magnetic field and flux measurements. Although the integral equilibrium relationship relating the sum of the average poloidal beta $\bar{\beta}_p$ and half the plasma inductance $\ell i/2$ to line integrals of the external magnetic field is well known,[1] an effective technique for separating $\bar{\beta}_p$ and ℓi has not been available. Statistically it has been shown that for sufficiently elongated plasmas $\bar{\beta}_p$ can be determined independent of ℓi.[2] However, the computational efforts involved there are extensive and require repeatedly solving the nonlinear Grad-Shafranov equation to search for the best fitted current density profile. Here, integral equilibrium relationships are derived which show that for noncircular plasmas, $\bar{\beta}_p$ and ℓi can be separately obtained from line integrals of the external magnetic field. The volume dependent parameters that appear can be evaluated approximately, allowing a rapid determination of approximate values of $\bar{\beta}_p$. Comparative calculations using Doublet III data are presented. The required plasma shape and poloidal magnetic field at the plasma boundary are determined from the measured external magnetic field and flux values by approximating the plasma current distribution using a few filaments.[3]

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*Work supported by U.S. DOE Contract DE-AT03-84ER51044.

OHM'S LAW RE-EXAMINED FOR LARGE MEAN FREE PATHS; A PRELIMINARY IMPLICATION FOR THE FIELD-REVERSED CONFIGURATION

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The rate of poloidal flux loss observed in Field-Reversed Configuration (FRC) experiments indicates that the resistivity at the field null may be somewhat larger than the classical Spitzer value. However, no plasma instability at the field null has yet been clearly identified as the cause of the large resistivity there. Therefore, we take the point of view here that microturbulence only exists away from the field null, on both sides, and we then investigate the effects of long electron mean free paths on Ohm's law at the field null.

A simple geometry is employed whereby a narrow low-collisionality slab is surrounded by large regions of high collisionality due to presumed microturbulence. Further simplifying assumptions are the neglect of the ambient magnetic field, and an isotropic scattering model. Within this context, the Boltzmann equation for the electrons is solved to provide the current-density response to an electric field along the direction of the slab (the toroidal direction of the FRC).

The result is that Ohm's law in the central low-collisionality region is always local, but that the high collision frequency characteristic of the external regions actually determines the central conductivity when the electron mean free path exceeds the width of the low-collisionality region. The preliminary implication for the FRC is that the resistivity at the field null could be directly determined by microturbulence away from the field null provided that the mean free paths in the central region are long enough to allow electrons to sample the surrounding turbulent regions.

Future work will include the effect of the ambient magnetic field on the zero-order electron orbits.

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Aurora

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A 1D-3V particle simulation code has been developed to study plasma behavior in an exact magnetic dipole field and a (B) field-aligned electrostatic (E) field. Currently research is being conducted to extend the work of Sato and Okuda[1] to an axial magnetic (mirror) field. The source plasma at the mirror midplane (x=L) is drifting Maxwellian ($T_e \sim T_i$) and at the mirror throat (x=0) is cold. Boundary conditions are $\Phi(x=0) = 0$, $E(x=L) = -d\Phi/dx|_{x=L} = 0$. Preliminary results suggest large potential changes along the field both at large ($L >> \lambda_D$) and small ($L \sim \lambda_D$) scale lengths.

Future study will concentrate on an off-axis system and extension of the code to 2D-3V.

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LOWER HYBRID HEATING STUDIES IN THE PRESENCE OF IMPURITY GENERATION IN THE ALCATOR C TOKAMAK*

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A simulation model has been developed for lower hybrid heating in the presence of RF generated, low Z (carbon) impurities. The model incorporates a radial transport code, a toroidal ray tracing code, and includes the effects of collisions, quasilinear diffusion, and the DC electric field on the electron distribution function.[1] Z_{eff} is taken to be constant across the plasma cross-section and is assumed to result from a fully ionized impurity with $A_I = 2Z_I$. The time evolutions of Z_{eff} and the electron density during RF injection are taken into account. The model has been applied to recent lower hybrid heating experiments on the Alcator C tokamak in which $\gtrsim$ 850 KW of RF power was injected into deuterium discharges constrained by silicon-carbide coated graphite limiters.[2] During RF injection a large increase was observed in carbon impurities along with large increases in Z_{eff} (from 1.5 to 5.0).[2] Code results indicate that for RF powers $\approx$ 850 KW and at line average densities $\bar{n}_e \simeq 1.3\times10^{14}$ cm^{-3}, increases in the central electron and ion temperatures of $\Delta T_{eo} \approx \Delta T_{io} \simeq 1$ keV can be achieved (in agreement with experiment). Numerical results also indicate roughly 500 KW of RF is deposited in the inner half of the plasma (r $\lesssim$ 8 cm) and the remaining 350 KW is absorbed via collisional damping at the plasma edge. These temperature rises are in part due to RF injection and in part due to low Z impurity generation.

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LINEAR NON-STOCHASTIC HEATING BY PERPENDICULARLY PROPAGATING ELECTROSTATIC WAVES*

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Significant perpendicular heating of ions or electrons by small amplitude electrostatic waves is demonstrated analytically, and in particle simulations for wave frequencies that are near a low multiple of the cyclotron frequency and wave phase velocity near the thermal velocity. The mechanism for this heating is basically linear and non-stochastic and is distinguished from stochastic heating by its characteristic outwardly spiraling particle orbits. The maximum velocity gain is larger than in an unmagnetized plasma and is in-dependent of the wave amplitude when exact resonance occurs ($\omega - n\omega_c = 0$). For a mismatch of frequencies ($\omega - n\omega c = \Delta\omega$), the maximum energy obtained depends on the amplitude of the driving electric field and on $\Delta\omega$.

Recent computer simulations exhibit the heating mechanism. In these simulations the heating is sufficient to saturate the instability caused by a velocity-space shell distribution of hot particles superimposed on a colder Maxwellian background.

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RESONANT TRANSPORT OF THE PLASMA IONS IN A BUMPY TORUS

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ABSTRACT

A new resonant transport mechanism is found which can enhance the diffusion rate of thermal ions in EBT geometry to the level of the electron diffusion rate. The periodic motion of the ions parallel to the magnetic field can resonate with the poloidal ExB motion and create uncompensated toroidal drift. Three different transport regimes are identified: collisionless resonant, plateau, and collisional; and analytic estimates of the diffusion rates are given. Applications to EBT-S and EBS (ELMO Bumpy Square) devices are discussed together with possible methods to suppress such enhanced transport.

CANONICAL MAGNETIC HAMILTONIAN*

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The canonical Hamiltonian description of a magnetic field provides a fundamental basis for understanding the theory of toroidal plasmas. If ϕ is any toroidal and θ any poloidal angle, the canonical form for the field is

$$\vec{B} = \vec{\nabla}\psi \times \vec{\nabla}\theta + \vec{\nabla}\phi \times \vec{\nabla}\Psi_p(\psi,\theta,\phi)$$

It is called canonical for field lines are given by Hamiltonian's equations

$$\frac{d\theta}{d\phi} = \frac{\partial\Psi_p}{\partial\psi} \qquad\qquad \frac{d\psi}{d\phi} = -\frac{\partial\Psi_p}{\partial\theta} .$$

There are two parts to the canonical description, the magnetic Hamiltonian Ψ_p (ψ, θ, ϕ) and the transformation equations to ordinary spacial coordinates $\vec{x}$ (ψ, θ, ϕ). Topological properties of the field are described by Ψ_p alone. Ideally stable equilibria are a minimum of the energy under variation of the transformation equations with fixed magnetic Hamiltonian. Tearing modes occur if the energy minimum is sensitive to small changes in the magnetic Hamiltonian. Faraday's Law is equivalent to

$$\vec{E} + \frac{\vec{V}_B}{c} \times \vec{B} = -\frac{\partial\Psi_p}{\partial t}\vec{\nabla}\phi - \vec{\nabla}\frac{\partial G}{\partial t}$$

with $\vec{V}_B = \partial\vec{x}/\partial t$ and partial derivatives taken in ψ, θ, ϕ, t coordinates. G represents the freedom to change gauge. An implication is that an integrable field remains integrable if and only if $\oint\vec{E}\cdot d\vec{\ell}$ is identical on every field line of each rational surface.

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NEOCLASSICAL ION TRANSPORT THROUGH THE SEPARATRIX IN DIVERTOR TOKAMAKS*

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Neoclassical ion heat transport through the separatrix[1] is studied for ions in the collisionless regime including the effect of trapped ions. Ion-ion collisions are assumed to be described by the pitch angle scattering operator. A variational expression is obtained for the ion heat flux through the separatrix. The trial ion distribution f is assumed to vanish on loss orbits which drift through the separatrix into the divertor plate. It is also required to match the neoclassical ion distribution function resulting from diffusion from inside of the plasma. The effect of electrostatic potential variation has been ignored. The resultant temperature scale length is comparable to the ion banana width and consistent with the temperature profile in H-mode discharges.

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ANALYTIC REPRESENTATION FOR FORCE-FREE FIELDS IN AN RFP WITH FOUR-NODE POLOIDAL DIVERTOR*

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Abstract

We are investigating reversed-field-pinch equilibria satisfying $\nabla\times\underline{B}=\lambda\underline{B}$ for plasmas bounded by a square conducting shell and containing a magnetic separatrix, i.e., a poloidal divertor configuration. To this end, we have extended an earlier work[1] which permits analytic solution of the flux contours. Such configurations are applicable to the Tokapole II device operated as an RFP and to aspects of the proposed Wisconsin RFP. In addition to the force-free plasma current, the calculation also includes four fixed filamentary currents which result in formation of the magnetic separatrix. The proposed Wisconsin RFP has been designed to elucidate the effects of boundary conditions, including the case of a magnetic limiter or separatrix boundary, on the dynamics of an RFP. Flux plots of our idealized model will be shown.

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SHERWOOD THEORY MEETING 1984

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ELECTRON RESPONSE TO ELECTROMAGNETIC PERTURBATIONS IN TOROIDAL PLASMAS*

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The linear stability of various electromagnetic perturbations, such as the tearing mode, depends on details of the electron response which are inadequately represented by collisional resistivity. At high temperature, electron trapping becomes important[1], while, for sufficiently low frequency and high beta, electron temperature gradients can have dramatic effects[2]. Here, a frequency and wavelength dependent Ohm's law is constructed which is appropriate for regimes in which $\omega_b \gg \nu \geq \omega$, where ω_b is the electron bounce frequency and ν is the Coulomb collision frequency. This ordering is often characteristic of tearing modes in hot tokamak plasmas. The kinetic theory is simplified by use of the ballooning representation. Electron temperature gradients are consistently treated by retaining collisional modifications in the electron distribution function. A variational procedure is used to obtain an expression for the generalized conductivity, allowing for trapping and other long mean free path effects.

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CONFIGURATION DEPENDENCE OF THE H-MODE*

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In the Doublet III tokamak, expanded boundary configurations are made which exhibit the enhanced confinement associated with the H-mode.[1] These configurations are bounded by a separatrix which limits the plasma 2 cm away from both the wall and the limiters. The orientation of the separatrix near the x-point (hyperbolic axis) is important in determining the stability of the plasma to ideal ballooning modes.

Two expanded boundary equilibria are analyzed, one with the orthogonal poloidal ray from the elliptic axis to the hyperbolic axis pointing toward the toroidal axis, and one with the poloidal ray pointing away from the toroidal axis.

The first case has good curvature at the x-point and is able to sustain a larger pressure gradient stable to ballooning modes than the second case, which has bad curvature at the x-point. If the destabilization is sufficiently strong, the second case will have increased edge transport and will be reduced to an "L" mode.

Both cases are analyzed for stability to ideal ballooning modes. It is shown that the degree of enhanced stability depends on the sign and magnitude of the toroidal curvature at the x-point. In addition to quantifying the effect of the orientation of the x-point on ballooning stability, an expanded boundary configuration is shown which is sufficiently unstable to ballooning modes near the plasma surface that the enhanced transport will decrease the confinement time to that of the "L" mode regime.

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*Work supported by U.S. DOE Contract DE-AT03-84ER53158.

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AN ALGORITHM FOR FINDING THE MAGNETIC AXIS

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ABSTRACT

According to theories such as those of Taylor and Shafranov, the equilibrium magnetic flux surfaces in toroidal reversed field pinch machines (e.g. the ZT-40M) are tubes whose poloidal cross sections are well-approximated by nested nonconcentric circles. If one assumes that plasma density is constant on these surfaces, then it is necessary to understand this geometry in order to use multichord laser interferometer measurements effectively. More specifically, one requires knowledge of $\delta(r)$, the position of the center of the circle of radius r, $0 \leq r \leq R_{boundary}$. Of special interest is the location of the magnetic axis, $\delta(0)$.

An algorithm is developed for obtaining $\delta(r)$ in terms of various moments of the chord integrated electron densities I_n. For small $\delta(0)/R_{boundary}$, the problem can be linearized and easily solved. Numerical experiments have been performed in which both $\delta(r)$ and the plasma density are assumed, the densities I_n are generated, and $\delta(r)$ is then recovered by use of the algorithm. Results, especially for $\delta(0)$, are very promising. The method has also been tried on actual ZT-40M data.

SUPPRESSION OF SPECTRAL POLLLUTION BY ANGLE RENORMALIZATION*

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It has been previously conjectured[1] that the Fourier spectra of the cylindrical coordinates (R,Z) describing MHD equilibria (inverse mapping) can be significantly compressed by an appropriate choice for the poloidal angle θ. By considering mappings of the form $\theta_* = \theta + \lambda(\theta,\phi)$, where λ is a periodic function of (θ,ϕ) and θ_* is the poloidal flux coordinate for which $\vec{B} \cdot \nabla\theta_*/\vec{B} \cdot \nabla\phi = \iota(\rho)$, the respective spectra in the θ_* and θ representations can be related by a formula corresponding to spatial frequency modulation of R_θ and Z_θ, with a modulation index equal to λ. Thus, for $|\lambda| \to 1$, broadening (pollution) of the θ_* spectra occurs. Examples which depict the spectral effects of increasing β (plasma shift) and shaping of the plasma boundary are considered. In two dimensions, the diagnostic $\partial(R^2/\sqrt{g})/\partial\theta_* = 0$ is used to check our results.

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MHD EQUILIBRIUM STUDIES OF A POLOIDAL DIVERTOR TOKAMAK USING THE CHODURA-SCHLÜTER METHOD*

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The Wisconsin Tokapole II is a poloidal divertor configuration tokamak with a considerable amount of plasma residing outside the separatrix. To help us understand resistive MHD instabilities in such a geometry, a numerical code has been developed to find MHD equilibria in a Tokapole-type device including plasma pressure outside the separatrix. The code employs the basic features of the Chodura-Schlüter method for an axisymmetric plasma in which a set of 2D MHF (magneto-hydro-friction) equations is numerically advanced to relax the plasma into an equilibrium configuration. This method is advantageous over the standard Grad-Shafranov approach in that the multivaluedness of the pressure (p) and poloidal current (I) functions with respect to the poloidal flux need be considered only in the initialization procedure. In addition to the fictitious friction force, a small resistivity is introduced to suppress numerical instabilities of the toroidal current density that tend to make the code numerically unstable. A small viscosity is also added to smooth ripples in the pressure. A parameter survey is conducted to investigate the effects of the divertor position and the plasma outside the separatrix on equilibrium.

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AN ANALYSIS OF A LOW FREQUENCY OSCILLATING FIELD CURRENT DRIVE OF AN RFP*

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Abstract

A current drive scheme,[1,2,3,4] known as F-Theta pumping, utilizing economic audio frequency ac modulation of the currents in the toroidal and poloidal field coils of a Reversed Field Pinch (RFP) is explored both analytically and numerically. The model[5,6] used is based on the assumption of a continuous plasma relaxation to an RFP state corresponding to a specific F-Theta curve. The nonlinear differential equation describing the coupling, via the plasma, of the poloidal and toroidal coil currents and voltages is studied, for the ac steady state, using small signal analysis. The analysis leads to a high degree polynomial whose real roots give the allowable values for the dc component of the toroidal plasma current for given operating conditions with specified amplitudes of the ac driving voltages. The results of parametric studies and the implications of the results on the viability of the scheme will be presented. Some comparisons of the theory with preliminary experiments[7] on the ZT-40M experiment and with the direct numrical solutions of the differential equation will be made.

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*Work performed under the auspices of the U.S. Department of Energy.

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1984 SHERWOOD THEORY MEETING
Incline Village, Nevada; April 11-13, 1984

STEADY STATE SOLUTION OF THE FOKKER-PLANCK EQUATION COMBINED WITH UNIDIRECTIONAL QUASILINEAR DIFFUSION UNDER DETAILED BALANCE CONDITIONS *

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The relativistic Fokker-Planck equation combined with RF diffusion has been solved for arbitrary values of RF diffusion coefficient under conditions of detailed balance of the stationary joint distribution involved [1]. The relativistic Fokker-Planck operator has been derived as the Landau limit of the relativistic Balescu-Lenard collision operator [2]. The solution of the combined Fokker-Planck and RF diffusion is in closed form and therefore easily amenable to various analyses (small or large diffusion coefficients, etc.) as in calculating current generated and power dissipated. The detailed balance condition also provides useful information about the functional form of the diffusion coefficients which are associated with the existence of a stationary steady state. The latter is also associated with a saturated spectrum of fluctuation in a plasma driven by a lower hybrid spectrum. Furhermore, the solution so obtained is used in formulating a variational principle for the fluxes analogous to the one which concerns the principle of the least dissipation of energy [3]. The possibility of using the solution under detailed balance conditions in a perturbation scheme for obtaining a class of more general solutions is also investigated.

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ORAL PRESENTATION REQUESTED

SHERWOOD THEORY MEETING 1984

April 11 to 13

STRONG TURBULENT THEORY OF ALFVEN WAVES

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An approximate closure scheme for steady state strong turbulence based on a scale separation (in ω-k space) between the coherent and incoherent response of the medium is developed. The scheme is tested by comparing the calculated steady state spectrum with the known exact result of a model problem[1]. The spectrum of magnetohydrodynamic Alfven waves ($S_{k,\omega}$) is calculated and the results compared with simulation studies[2] and weak turbulence theories.

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DEUTERIUM RECYCLING IN ZT-40M REVERSED-FIELD PINCH*

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Deuterium atoms or ions that impinge on a metal wall, such as the inconel vacuum vessel of ZT-40M do not reflect specularly. Rather, the particles enter the near-surface lattice of the metal, suffer multiple scattering by the lattice sites, and slow-down on the electrons. Backscattered particles emerge from the lattice after many collisions with the lattice sites and after significant energy loss. Particles that are not backscattered come to rest within the lattice—they are implanted. This implantation produces a spatial concentration of deuterium within the metal.

The deuterium concentration in the metal obeys the diffusion equation, where the diffusion constant is a property of the material and the implanted particle. Deuterium atoms that diffuse to the surface of the metal are not released directly. Rather, the atoms recombine to form deuterium molecules that escape. In tokamak experiments the overall rate for deuterium recycling is limited by the process of molecular recombination at the surface. However, in ZT-40M discharges the time scale is shorter, the flux of deuterium incident on the wall is much larger and the recycling rate is limited by diffusion rather than molecular recombination. In this case, the dependence upon the wall temperature of the deuterium recycling rate is very different from that which is recombination limited. Results illustrating the dependence of the recycling rate upon the wall temperature and upon the diffusing species will be presented and compared with data from ZT-40M.

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THE EARLY TIME BEHAVIOR OF LOWER HYBRID CURRENT DRIVE*

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We use a realistic analytical and numerical model[1] for lower hybrid heating and current generation to simulate the early time behavior of current drive experiments before steady state is reached at a small fraction of the plasma L/R time. The model incorporates a 1-D radial transport code, a toroidal ray tracing code, and a relativistic quasilinear calculation of the longitudinal electron distribution function in the presence of RF waves, a DC electric field, and an energy dependent loss rate. Spatial diffusion equations for parallel current density components carried by high velocity resonant electrons are advanced simultaneously with the equations of the transport code. Results from time dependent 2-D Fokker-Planck calculations[2] are included phenomenologically in the model.

*Work supported by United States Department of Energy.

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SHERWOOD THEORY MEETING 1984

April 11 to 13

Quasilinear Evolution of Tearing Modes*

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A theoretical model is developed for the quasilinear evolution of tearing mode turbulence for a current sheet with field reversal taken as $B_y(x) = B_y^o \tanh (x/\Delta)$. The unstable spectrum $k_y\Delta < 1$ is shown to produce an inward transport of mangetic flux that gives rise to an effective anomalous resistivity η_a which is positive definite. It is shown that η_a exceeds the collisional resistivity η_o when the magnetic turbulence exceeds the low level given by $\delta\tilde{B}_\perp/B_y^o \sim \varepsilon^{3/5}$ where $\varepsilon = \tau_A/\tau_r$ with $\tau_A = \Delta/(4\pi\, m_i n)^{1/2} B_y^o$ and $\tau_r = \Delta^2/\eta_o$. For $\delta\tilde{B}_\perp/B_y^o > \varepsilon^{3/5}$ the propagator $(\gamma + k_\perp^2\eta)^{-1}$ must contain the renormalized resistivity and the effect is to change the exponential growth of the mode to an algebraic growth in time.

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NONLOCAL DC ELECTRICAL CONDUCTIVITY OF A LORENTZ PLASMA IN A STOCHASTIC MAGNETIC FIELD

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ABSTRACT

The stochastic wandering of magnetic field lines allows momentum of even perfectly magnetized electrons to be transported across the mean $\vec{B}$. We include this effect, along with the usual acceleration and scattering terms, in a spatially one-dimensional Boltzmann equation for the electron distribution function. For an electric field $E_{\parallel}$ (along local $\vec{B}$) which varies versus position normal to $\vec{B}$, the momentum transport leads to a nonlocal electrical conductivity. We apply the formalism to sheared, force-free magnetoplasmas, in which the $E_{\parallel}$-gradient is caused by variable twisting of $\vec{B}$ with respect to an externally applied uniform $\vec{E}$. We examine in particular the experimentally documented phenomenon of field-aligned current density $j_{\parallel} > 0$ in regions of the sheared magnetic field where $E_{\parallel} \simeq 0$ or even $E_{\parallel} < 0$. This phenomenon is in apparent violation of Ohm's law. Under suitable conditions of stochasticity and collisionality, we find that the spatial structure and temporal persistence of these force-free configurations can be directly caused by electron-momentum transport. This result is derived solely on the basis of electron dynamics. In contrast to fluid-turbulent models, our kinetic derivation requires no hypothetical "plasma dynamo" and no conjecture on the decay-rates of magnetic helicity versus magnetic energy.

SHERWOOD THEORY MEETING 1984

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SUSTAINED REVERSAL OF A REVERSED FIELD PINCH

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In toroidal pinch experiments, the RFP (toroidal field reversed) state is observed to arise spontaneously and persist for many times the resistive diffusion time τ_R. Nonlinear mechanisms by which MHD activity of a pressureless plasma sustains the RFP state have been investigated by three-dimensional numerical simulations. Solutions of the incompressible resistive MHD equations have exhibited the generation and maintenance of a cylindrical RFP [1]. In these simulations, a steady or quasi-steady RFP state is produced by an initially ideal MHD unstable profile in a fraction of τ_R and maintained for the duration of the solution, up to one τ_R.

Recently, these results have been extended using a fully compressible implicit algorithm [2], for ideal MHD stable, tearing unstable initial conditions and for various values of aspect ratio A, resistivity S^{-1}, and viscosity ν. The scaling of magnetic fluctuations (deviations from cylindrical symmetry) with A and S is discussed. Predictions of saturation of m = 1 activity by cascade [3] or quasilinear modification of the equilibrium [4] are compared with simulation results. An examination of the m = 1 energetics and variation of the dissipation wavenumber (with ν) are used to distinguish these two mechanisms.

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THREE-DIMENSIONAL STUDIES OF COHERENT RESISTIVE MHD ACTIVITY IN THE REVERSED-FIELD PINCH

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Previous [1] single-helicity (two-dimensional) studies of the reversed-field pinch (RFP) have indicated that tearing instabilities with poloidal mode number m=1 and a range of toroidal mode numbers n ~ 5-20 play an important role in the dynamical evolution of the RFP. The nonlinear evolution of these single-helicity instabilities suggested that sawtooth oscillations, which have been observed [2], may be present in the RFP. However, it is necessary to study the nonlinear interaction of many modes because of the close spacing of m=1 resonances in typical RFP equilibrium profiles.

Three-dimensional studies of the RFP have been undertaken and results of these studies and comparisons to ZT-40M experimental data are presented. These new results show that the nonlinear interaction of many m=1 modes can give rise to a stochastic core, and that therefore energy confinement in the RFP may come largely from the edge region that retains good flux surfaces. These studies also show a strong nonlinear beating to the m=0 mode, resonant at the reversal surface, for equilibria with a high value of the pinch parameter theta, and an outward spreading of the inner stochastic core. In addition, the RFP dynamo effect (maintenance of the RFP field configuration against resistive diffusion) appears to have as its origin the nonlinear interaction of many m=1 modes.

The comparison of these results with experiment shows both agreement and departures from what theory would suggest. The observed sawtooth oscillations become larger in amplitude as theta is raised above 1.5, which can be explained in terms of the larger nonlinearly driven m=0 islands seen in the simulations at higher theta. However, a continuous m=1 oscillation in the soft X-rays that is caused by a single mode resonant close to the axis is observed on ZT-40M at lower theta values, and as a precursor to the sawtooth oscillations at high theta [3]. Such a structure may be unobservable if this region of the plasma were stochastic. Consequently, ZT-40M may have better flux surfaces than the simulations indicate. The observed coherent MHD activity on ZT-40M is unlike HBTX1A where experimental studies show no coherent oscillations [4] (sawtooth or continuous). The reasons for this difference may be due to the sensitivity of the RFP to external magnetic field errors.

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The Dynamo Effect in Fusion Plasmas

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The mean magnetic field $\langle \mathbf{B} \rangle$ in a low beta plasma satisfies, in steady state, $\langle \mathbf{J} \rangle \times \langle \mathbf{B} \rangle \approx 0$ and $\eta \langle \mathbf{J} \rangle \cdot \langle \mathbf{B} \rangle = \langle \mathbf{E} \rangle \cdot \langle \mathbf{B} \rangle$ where η is the resistivity and $\mathbf{E}$ is the electric field. If $\mathbf{E}$ is an applied axial field in a cylindrical pinch, $E_\theta = 0$, E_z = constant, field reversed solutions do not exist in general. A reversal of B_z can occur if the averaged electric field due to magnetofluid fluctuations is taken into account,

$$\langle \mathbf{E} \rangle = E_z \nabla z + \langle \hat{\mathbf{v}} \times \hat{\mathbf{B}} \rangle , \qquad \hat{\mathbf{B}} = \mathbf{B} - \langle \mathbf{B} \rangle .$$

The fluctuating contribution can be easily calculated in the case of kink tearing modes and shown to have the correct sign to provide field reversal in RFP's, negative voltage spikes in tokamak disruptions, and a saturation mechanism for m = 1 tearing modes.

A more quantitative study has been carried out using reduced MHD equations, based on a new ordering in $|\hat{\mathbf{B}}|/|\langle \mathbf{B} \rangle|$, which is small in most experiments. The equations for the fluctuating velocity $\hat{\mathbf{v}}$ and magnetic field $\hat{\mathbf{B}}$ are essentially linearized resistive MHD except for the shear Alfvèn line bending terms, which vanish at rational surfaces unless nonlinear corrections are included. The fluctuations give rise to the dynamo term $\langle \hat{\mathbf{v}} \times \hat{\mathbf{B}} \rangle \cdot \langle \mathbf{B} \rangle$ used in the evolution of the mean field. In the appropriate limit, the equations become tokamak reduced MHD.

Numerical time dependent solutions show a quasi steady turbulent dynamo producing field reversal for pinch parameter $\theta \gtrsim 1.5$. The mean magnetic field is unstable to m = 1 tearing modes, which generate an averaged electric field and cause field reversal. Turbulence is produced by the interaction of several modes.

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Drift Wave Turbulence and Experimental Confinement Scaling*

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A model for anomalous electron heat conduction in tokamaks is proposed and analyzed to obtain the scaling of electron energy confinement time and temperature with magnetic field, size, etc. The model supposes strong drift wave turbulence, turbulent diffusion of magnetically trapped electrons, and utilizes the experimental observation that effective thermal insulation in tokamaks exists only between the q = 1 and q = 2 surfaces. Two regimes are identified: collisional with $\nu_{eff} > \omega^*$ and collisionless with $\nu_{eff} < \omega^*$. Ohmic heating experiments are often in the collisional regime where the model predicts that the electron energy confinement time will scale as $\tau_{Ee} \propto nB^{-0.02} a^{1.67} R^{1.48} I^{-0.31} Z^{-0.16}$. Beam-heated discharges are collisionless and the confinement time scaling is $\tau_{Ee} \propto I^{0.7} R^{1.5} a^{0.8} n^{0.6} P^{-0.6} B^{0.1}$. Both scalings have significant agreement with recent summaries of experimental results.[1] Predictions for temperature and ignition parameter scaling will be given.

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Implications of Kinetic Instabilities For Anomalous Transport Modelling*

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Since anomalous transport models based on self-consistent theoretical methods remain to be developed for practical application to existent tokamak experiments, it is important to consider "semi-empirical" approaches. These generally involve the use of experimentally observed trends as a guide in choosing the dominant "first-principles" physics features modelled. The present study deals with the formulation of anomalous electron thermal transport coefficients (χ_e) which are consistent with global constraints on the current distribution as well as with onset conditions for the presence of the dominant kinetic instabilities. The prescription here involves the notion that the anomalous processes in the plasma tend to maintain MHD stable current profiles[1]. By prescribing this profile (approximately Gaussian-shaped) and a generalized form of Ohm's law to relate current to temperature, the energy balance equation is readily solved to provide a basic constraint condition on χ_e. Implications of these studies for confinement scaling trends are discussed.

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HIGH CURRENT IGNITION EXPERIMENTS*

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Numerical transport simulation of high current, small aspect ratio tokamaks using a variety of thermal transport models shows that Ohmic heating characteristics change significantly and that it may be possible to reach ignition conditions through Ohmic heating alone. In particular, a compact, highly elongated device ($R = 99$ cm, $a = 40.5$ cm, $b = 65$ cm) with $B_T = 100\text{-}130$ kG, and total current $I_p = 10.2$ MA ($B_p = 40$ kG) has extremely strong Ohmic heating. At 5-8 keV, half of the total Ohmic power is deposited in a region of width $\sim$ (1/5)a located mostly outside $r = (1/2)a$, while half is deposited within roughly $r = 0$ to $r \cong (1/2)a$. The Ohmic power densities (W/cm^3) are strongly peaked at or just outside $r \simeq (1/2)a$. Under sub-ignition conditions (where fusion heating is not important) the plasma heats rapidly to >5 keV once full current is attained (for D_2 as well as DT plasmas) and under certain transport models easily attains ignition temperatures. The heating is stronger than for another high current, tight aspect ratio design, Ignitor, although the current density and peak Ohmic power density is smaller in the present case. The heating and energy transport mechanisms are also compared to transport simulations of several current experiments.

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Ponderomotive Force Stabilization of Interchange-Ballooning Modes in Axisymmetric Mirrors*

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The theory of ponderomotive force due to an applied RF wave $\sim E(\underset{\sim}{r})\exp(ik_{\parallel}z - i\omega t)$ is examined from the perspective of several plasma descriptions. It is shown how the force on a single particle in a quasilinear kinetic description is related to the force on a fluid element. For a pure left-hand polarized electromagnetic ion-cyclotron wave with $k_{\parallel}v_i \ll \omega - \Omega$, the force on an ion fluid element is given by

$$\underset{\sim}{f} = -\frac{1}{8\pi}\underset{\sim}{\nabla}_{\perp}\left[\frac{\Omega\omega_{pi}^2|E|^2}{\omega(\omega-\Omega)^2}\right] - \frac{1}{8\pi}\frac{\omega_{pi}^2}{\omega(\omega-\Omega)}\underset{\sim}{\nabla}|E|^2$$

in agreement with fluid theory.[1] Retaining $\underset{\sim}{f}$ self-consistently in the ion momentum equation, a modified set of one-fluid (MHD) equations is obtained. Linearizing about a long-thin axisymmetric tandem mirror equilibrium with no rotational drive, it is shown that only the second term of $\underset{\sim}{f}$ contributes to the interchange-ballooning equation. It follows that interchange stability is sensitive to the sign of $\omega - \Omega$ in agreement with Phaedrus results. The correct treatment of the resonant denominator will be examined in some limiting cases, and an expression for $\underset{\sim}{f}$ taking into account resonant particles ($k_{\parallel}v_i \sim \omega - \Omega$) will be presented.

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*Work supported by U.S. Department of Energy contract DE-AC03-76-ET53057.

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CALCULATION OF MULTI-ION TRAPPING RATES IN TANDEM MIRROR END CELLS*

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Maintenance of a thermal barrier and MHD stability in tandem mirrors requires continual pumping of ions that become trapped in the end cells. In order to know how fast to pump these trapped ions, it is necessary to ascertain the rate at which they are being trapped. We present here results from the two-dimensional, nonlinear, multispecies Hybrid-II code which uses the square-well approximation.[1] The equations solved are $(\partial f_a/\partial t)_{FP} = \nu_a f_a$ subject to the boundary condition $f_a = f_a^{pass}$ at the trapped/passing separatrix in velocity space. Here f_a is the distribution function of trapped species a and ν_a is the pumping rate. The mirror ratio, potential and passing temperature (same for all species) are specified. The calculations proceed either by specifying ν_a, which would be approximately the same for all species if drift pumping is used, or by specifying $g_a = 1 + n_a/n_a^{pass}$ in the square well. Initial studies looked at single species of ions with differing charge and mass. Results for the trapping rate $(dn_a/dt)_t$ show deviations from the scaling $\propto z^4/\sqrt{m}$ which follows from single-ion scattering. A stronger increase for heavier ions is indicated. Multi-ion cases with D^+, T^+ and He^{++} have been run and show that drag on ions of differing charge/mass is important in determining the trapping rate. Lower charge/mass moves the trapped/passing separatrix to lower velocity; thus drag of D^+ on T^+ increases the D^+ trapping rate but lowers the T^+ rate. Multi-species generalizations of the single-species expressions of Futch and LoDestro[2] have been developed and are applied to the results.

[1] J. Killeen, A. A. Mirin and M. E. Rensink, in: Methods in Computational Physics, 16, Academic Press, New York (1976).

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High Frequency Stability of the Precessional Mode in a Hot Electron Symmetric Tandem Mirror*

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It is well known that the precessional mode in a hot electron symmetric tandem mirror can be unstable[1] when the length or density of the center cell is large enough. All analyses leading to this conclusion assume the hot electron curvature drift frequency, ω_{kh}, is much smaller than the ion cyclotron frequency, Ω_i.

Using general frequency gyrokinetic technique, we have derived a dispersion relation for the precessional mode when ω_{kh} is of the same order as Ω_i. Finite ion gyro-radius effects are retained. There are two Ω_i effects that help to stabilize the precessional mode. In the center cell the shear Alfven frequency has a cutoff at Ω_i. If ω_{kh} is larger than Ω_i of the cneter cell, then the frequency matching condition cannot be satisfied and ths system is stable. However, this stabilization mechanism is not feasible when center cell ion FLR effects are important, because modes around the harmonics of Ω_i will appear.

The second effect is related to the compressional Alfven modes in the end cells which were ignored in previous investigations. When $\omega_{kh} \sim \Omega_i$, the magnetosonic effect eliminates the precessional singularity in the dispersion function and hence the free energy available for instability. This stabilization mechanism is not affected by the ion FLR effects.

The effects of multiple ion species will also be discussed.

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*Work supported by U.S. Department of Energy contract DE-AC03-76-ET53057.

[1]D. E. Baldwin and H. L. Berk, Phys. Fluids 26, 3595 (1983).

Excitation of Ion Bernstein Modes from Density Fluctuations during ICRF Heating of Tokamaks*

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This study considers the interaction of a fast Alfven wave of frequency $\omega_o(\Omega_i < \omega_o < 2\Omega_i)$ with pre-existing low frequency ($\omega \approx 0$) density fluctuations characteristic of the drift-wave type of turbulence observed in tokamaks, i.e., having $k_\perp \rho_i \sim 1$ and small $k_\parallel$. The excitation process, previously labelled direct conversion[1], consists of the beat of the long wavelength oscillatory velocity, imposed on the ions by the fast wave, with the density fluctuations to generate a source current that can resonantly drive ion Bernstein modes. In the uniform plasma limit, away from cyclotron resonances, the amplitude of the Bernstein mode is limited by electron Landau damping, which is governed by the parameter $\overline{\xi} = \Omega_i/(k_\parallel)_o \overline{v}_e$. For $\overline{\xi} \geq 3$, as may be attained in large devices or near the plasma edge, significant fast wave damping can result due to this process. In such a case, plasma nonuniformities must be retained. Relevant analysis indicates that the amplitude of the Bernstein mode is limited by convection out of the finite size excitation region determined by the overlap of the density fluctuation eigenfunction with the Bernstein mode Airy pattern near its propagation cut-off.

1. A. Y. Wong, G. J. Morales, D. Eggleston, J. Santoru, and R. Behnke, Phys. Rev. Lett. 47, 1340 (1981)

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ELECTROSTATIC CONFINEMENT IN A BUMPY TORUS WITH HOT ELECTRON RINGS*

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We have analyzed the equilibrium of a bumpy torus in the presence of an ambipolar potential. Previous work neglecting the effects of the potential showed that the pressure P is a function of $U \equiv \oint d\ell/B$.[1] A different picture emerges when the charge-independent $\vec{E} \times \vec{B}$ poloidal drift is no longer negligible in comparison with the magnetic precession. Charge separation would then result generally if an ion polarization drift did not arise. The drift kinetic equation can be used in the collisionless constant temperature limit to show that $P = g(e\phi/T_e + \ell nU)/U$ where g is an arbitrary function, ϕ is the electrostatic potential, e is the magnitude of the electron charge, and T_e is the electron temperature. Besides, the quasineutrality condition turns out to be equivalent to solving the equation $\vec{\nabla} \cdot \vec{D} = \rho_f$ where $\vec{D}$ is the displacement vector in the high plasma density limit and ρ_f is the net charge obtained using the drift kinetic equation, excluding only the ion polarization. To insure quasineutrality in the hot electron ring region, we assume that the outermost equipotential coincides with the ring boundary. The solution to the above partial differential equation shows an asymmetry in the potential caused by the toroidal magnetic curvature which forms a pressure-dependent electrostatic dipole along the major radius (analogous to the Pfirsch-Schlüter current in a tokamak). Formation of potential islands occurs when $(T_e + T_i)$ exceeds $2ML_nR\Omega^2$, where M is the ion mass, L_n is the density scale length, R is the major radius, and Ω is the $\vec{E} \times \vec{B}$ precession frequency. Because of its effect on equilibrium, it is obvious that taking the ion polarization into account should have important effects on both the stability and radial transport of the toroidal plasma.

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RESISTIVE MHD-LIKE EQUATIONS IN THE BANANA-PLATEAU COLLISIONALITY REGIME*

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We are continuing our work[1,2] attempting to derive resistive MHD-like equations in a banana-plateau or long mean free path collisionality regime. The dominant physical feature arising in the banana-plateau regime is the viscous damping of the poloidal flow embodied in modes that are highly extended along the magnetic field, but radially well localized. In this paper we will discuss how this long mean free path flow damping mechanism couples the parallel and perpendicular (geodesic curvature driven) compressibility effects in the usual resistive MHD equations and thus should lead to a significant modification of the compressibility effects on resistive MHD instabilities.

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[1] J.D. Callen and K.C. Shaing, paper 1E3, Sherwood Meeting, March 21-33, 1983, Arlington, VA.

[2] K.C. Shaing and J.D. Callen, Bull. Am. Phys. Soc. 28, 1213 (1983).

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LOW FREQUENCY STABILITY OF AXISYMMETRIC TANDEMS WITH HOT ELECTRONS*

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Further axisymmetric tandem mirror stability studies with the FLORA code are reported. FLORA is an initial-value code and integrates an equation of motion for the evolution of an incompressible linear perturbation of a long-thin, finite-beta tandem mirror equilibrium which varies in ψ and z flux variables. Perturbations are Fourier analyzed in angle. Finite-Larmor-radius (FLR) modifications are included using Newcomb's formalism. The equation of motion describes the dynamics of ballooning, interchange, and rotational low frequency modes. The code has been exhaustively checked against other numerical calculations of rotational modes and against analytical calculations of curvature-driven modes with FLR effects for special profiles.

We have used FLORA to study the low-frequency stability of a generic axisymmetric tandem mirror. We have included the stabilizing influence of a hot electron ring in the rigid limit and determined stable ring and plasma pressure profiles. We are in the process of applying FLORA to the UCLA-TRW AXIM proposal, TARA, and Phaedrus in the "stand-alone" mode. The equation of motion describing the coupling of hot-electron precessional modes in the plugs with shear Alfvén waves in the center cell has been formulated, and modification of FLORA is discussed. We are also applying FLORA to the study of rotation-driven modes with highly sheared drift profiles, which may be influential in the center cells of tandem mirrors.

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INFLUENCE OF ION CYCLOTRON HEATING ON INTERCHANGE STABILITY*

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This paper presents a simple two-fluid analytical study of the effects of ion cyclotron heating on the interchange stability of a magnetized plasma. This study is motivated by experimental findings on the Kyoto University axisymmetric mirror and the University of Wisconsin Phaedrus tandem mirror in the "stand-alone" mode that indicate the suppression of magneto-hydrodynamic fluctuations in the presence of ion cyclotron heating. In particular, the MHD fluctuations in Phaedrus are sensitive to whether the frequency of the applied radio frequency waves is near ion cyclotron resonance.

We derive a dispersion relation for interchange modes in a standard slab configuration including the nonlinear modifications produced by ponderomotive action of the ion cyclotron waves and by coupling of the interchange mode to upper and lower frequency sidebands of the ion cyclotron wave. The principal ponderomotive effect seems to arise from the ion drift perpendicular to $\vec{B}$ induced by the $-m\vec{v} \cdot \nabla\vec{v}$ ponderomotive force. The sideband coupling also modifies the interchange dispersion relation at second order in the field amplitude of the ion cyclotron wave. We have examined both electron and ion nonlinearities in the sideband calculation. We are also using B. McVey's antenna code and making some analytical evaluation of the ion cyclotron fields in the plasma to determine the influence of ICRH wave penetration on the nonlinear modification of interchange stability. For Phaedrus parameters, our calculations indicate that ponderomotive effects and sideband coupling have a very potent stabilizing influence on simple interchanges. We will also compare our analytical calculations with others and comment on some differences.

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Modeling of ICRH Heating in TMX-U*

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Recent results from TMX-U suggest that ICRH heating produces a highly anisotropic central cell ion distribution function. We are trying to understand these results by applying two tools: (1) A single region bounce-averaged Fokker-Planck code with quasi-linear r.f. diffusion and fluid electrons, and (2) a time-dependent 0-d two fluid model assuming bi-Maxwellian ions. The results we have gotten so far seem fairly consistent with the diamagnetic loop observations, although assumptions on the fueling and electron dynamics seem critical and modeling them needs further work. Results will be presented.

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NONLINEAR SATURATION OF SINGLE MODE DISSIPATIVE TRAPPED PARTICLE INSTABILITY*

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The dissipative trapped particle instability (trapped ion mode) is expected in tokamaks, TMX-U type tandem mirrors and has been observed and identified in the Columbia linear machine. In the Columbia linear machine it appears as a single mode (of azimuthal mode number m=1) and in TMX-U the same may be expected. Modelling the signficiant radial variation of density gradient as parabolic in form, a nonlocal linear analysis in slab model yields Weber type eigenfunctions. The nonlinear wave potential, due to polarization and $\overline{E}x\overline{B}$ nonlinearities, is then expanded in terms of these eigenfunctions involving fundamental (n=0) and first order (n=1) radial Hermite functions. Using 3-wave nonresonant mode coupling, these equations are reduced to two mode coupling equations for the fundamental and first order radial harmonic. The solution of these coupled equations yields the nonlinear saturation level of the unstable (n=0, m=1) mode. The principal physical saturation mechanism is the energy drain via mode coupling to damped higher order radial modes. The resulting saturation level $\tilde{n}/N_0 \sim 15\%$ for the parameters of the Columbia linear machine, agrees with the experimental data.

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PHYSICS OVERVIEW OF THE ELMO BUMPY SQUARE*

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The ELMO Bumpy Square (EBS) is formed by four linear arrays of simple magnetic mirrors linked by four high-field toroidal solenoids (corners). The EBS configuration offers a number of distinct advantages over a conventional EBT with respect to particle confinement, heating, transport, ring production, and stability. In EBS the particle drift orbits are nearly concentric for trapped and passing particles. The velocity space loss region for transitional particles (near the boundary between trapped and passing zones) at high energy is greatly reduced leading to improved volume utilization, significantly reduced direct particle losses, and increased microwave heating efficiency. For an isotropic distribution, more than 95% of the particles are confined in EBS as compared to ~50% confinement in EBT-I/S. The combination of nearly concentric particle drift orbits and the small radial displacements in the high field corners give an order of magnitude reduction in neoclassical diffusive losses. The orbits of the deeply trapped particles ($V_{\parallel}/V = 0$) and core plasma pressure surfaces ($\oint d\ell/B$ contours) almost coincide and are centered on the minor axis. There being no shift, hot electron rings will be exceedingly well centered in EBS. For the same anisotropy ($V_{\perp}/V_{\parallel}$) in EBS there should be little or none of the radial broadening of the ring that occurs in EBT. This should make it easier to form an average magnetic well in EBS than in EBT. Detailed calculations in the areas of equilibrium and stability indicate that equilibria exist (shifts are smaller in a square configuration than in a torus) and the stability limits (especially those asociated with the corners) are no more restrictive than those studied for a conventional EBT. Reactor projections for EBT indicate the possibility of a substantial reduction in reactor physical size (a factor of 2–3) as compared to past EBT designs.

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Incompressible M.H.D. Modes in Toroidal Geometry*

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The use of a nonlinear resistive M.H.D. model valid in the large aspect ratio limit has been successful in interpreting low frequency M.H.D. activity in high β tokamak plasmas with low power injection.[1] Recent experimental results[2] indicate that at high injection power the internal kink mode could play an important role. Since this instability cannot be studied with the reduced M.H.D. model,[3] a study was conducted using the full M.H.D. equations in the incompressible limit. The computer code FAR was constructed using these equations. A sequence of equilibria which differed in their β values was studied for stability to linear n=1 modes. At low β, the usual tearing modes of the reduced theory are visible. At intermediate β's ($1\% \leq \beta_0 \leq 15\%$, where β_0 is the value of β at the magnetic axis) the anticipated ideal internal kink modes are seen. Ideal internal kink means: 1) the mode structure is identical to the classical kink but is confined inside the q=1.0 surface and 2) the structure of the mode is basically unchanged when the resistivity is taken to zero. At values of β_0 above 15%, results identical to those from the reduced equations are recovered when modes with a resistive ballooning structure are unstable. The existence of a region at high β_0 where any deleterious effects due to the ideal internal kink may be avoided confirm results found using an analytic theory[4] and results from an ideal study.[5] Modes with higher toroidal wave number are now being investigated. Details of the above and calculational methods will be presented.

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†Computer Sciences at Oak Ridge National Laboratory.

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ENERGETIC ELECTRONS IN EBT*

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There is overwhelming evidence for the existence in EBT of substantial populations of electrons very much hotter than the bulk population. For example, when Thomson scattering (sensitive to energies $\lesssim$ 500 eV) indicates a bulk population of $T_0 \sim 100$ eV and of density n_0, soft x-ray detectors (most sensitive to energies $\gtrsim$ 1 keV) indicate a (tail) population of $T_T \gtrsim 300$ eV and density (0.2-0.5) n_0, while hard x-ray detectors show a (ring) population of $T_R \gtrsim 250$ keV, $n \sim 0.1\ n_0$. Further, these lower density populations appear to have serious consequences for EBT performance, with the appearance of the relativistic ring component signalling the onset of the quiescent regime, and the tail providing an energy channel for both absorption and loss.

In this paper we analyze the formation and subsequent properties of these energetic distributions, taking into account the radial structure of both heating geometry and particle drift surfaces. The calculation is based on taking moments of spatially segregated, line-averaged, Fokker-Planck equations describing appropriate heating and loss processes. Results include the spatial structure, density, and temperature of the very hot component, dependence of these quantities on magnetic field B, power requirements for formation of a hot component of $\beta \equiv 4\pi n T_e/B^2 > 5\%$, and scaling of that startup power with density, along with the electron distribution, equivalent temperature, and anisotropy of the > 300 eV tail component, and an estimate of the energy flow out of EBT due to this component (direct loss).

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Equilibrium and Axisymmetric Stability of the Columbia High-beta Tokamak*

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The Columbia High-Beta Tokamak (HBT), presently under construction, is a successor to the tokamak Torus II which demonstrated the ability to form a high-beta tokamak using a fast toroidal field reversal heating scheme.[1] Pulse lengths in Torus II were short (20 μsec) and the external current configuration produced highly unfavorable magnetic field curvature. With the insertion of a power-crowbar and a new Ohmic Heating (OH) and Vertical Field (VF) coil configuration the HBT device will be capable of having an externally supplied magnetic field pulse of 1 msec and favorable field line curvature. This work demonstrates that both circular and elongated plasmas can be formed in HBT and studies the problem of passively stabilizing the vertical instability in elongated configurations.

In both Torus II and HBT the OH and VF systems consist of a set of current carrying bars, not filament currents, so that the calculation of equilibria is slightly non-standard. An additional outer loop has been added to the PEST Equilibrium Code[2] which redistributes the external current distribution, at the end of a free boundary calculation, in such a way that each bar is a flux surface. In practice, 5 to 10 of these loops is sufficient to calculate low-beta, circular or elongated configuration. Various equlibria will be presented for HBT.

Jardin's[3] time dependent, axisymmetric, resistive MHD code has been modified to study the vertical instability in HBT elongated plasmas. The effect of positioning passive feedback loops around the vacuum vessel is examined and will be presented.

*Work supported by U.S. DOE Contract No. DE-AC02-76-ET-53016.

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HOW FAST IS FAST MAGNETIC RECONNECTION ACROSS AN X-TYPE NEUTRAL POINT ?

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Various disruptive magnetic processes occur by reconnection across an x-type neutral point, notably the m=1 sawtooth disruption. The most widely accepted theory of this reconnection process is the Petschek model with the basic property that the reconnection rate M is essentially independent of η, the value of the resistivity. Numerous numerical simulations of driven and spontaneously reconnecting systems performed in recent years, however, reveal a quite different behaviour. In the present paper it is now shown that Petschek-type models are in fact not valid for small η. This is due to the properties of the diffusion region (the small region around the x-point, where the resistivity is important), which are found to differ substantially from those assumed or calculated approximately by Petschek and others following his concept. Their essential assumption is that the transition from the diffusion region to the ideal field reversal or downstream region is smooth and that the plasma being accelerated along the diffusion layer up to the Alfven velocity v_A continues to flow at this speed. Actually the transition is not smooth which leads to strong local deceleration and downstream flow speed $v_1 \ll v_A$. The structure of the diffusion region as observed in numerical simulations is described in detail and an approximate analytical theory is given. As a consequence the reconnection rate is in general quite small, strongly dependent on η, which explains, for instance the fact that reconnection in the internal m=1 disruption is incomplete for small η. Only if the restrictions imposed by the diffusion region are loosened by allowing a local increase of η (anomalous resistivity), Petschek's configuration is recovered.

FOKKER-PLANCK MODELING OF ELECTRON CYCLOTRON HEATING AND DIRECT PARTICLE LOSS IN EBT AND ELMO BUMPY SQUARE*

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ABSTRACT

The SMOKES D-2 Fokker-Planck code has been used to investigate core plasma heating at the fundamental cyclotron resonance including a bounce-averaged quasilinear fundamental electron cyclotron heating operator and Coulomb collisions. It is found that heating depends very sensitively on details of the RF electric field profile. A profile is used which maintains consistency between the microwave power flux and the particle heating rate. Using this profile, we find that most of the RF power is absorbed by passing particles or energetic trapped particles which are transitional between trapped and passing, and tend to be poorly confined in EBT-S. In order to model the direct loss of these transitional particles on open drift surfaces, we introduce a lossy region in velocity space with particle lifetime $\tau_D(\varepsilon, \mu)$ = time for particles to drift out. We find that substantial power is lost directly. These processes show promise of explaining a number of experimental observations including the presence of an energetic, anisotropic, locally produced electron tail. Because the transitional particles in an Elmo Bumpy Square (EBS) devices are removed in velocity space from the heating zone and because the lossy region associated with transitional particles is much narrower than in the bumpy torus, ECH in the EBS should be much more efficient than in EBT-S.

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Computer Evaluation of the Magnetic Field Line Hamiltonian*

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The magnetic field line Hamiltonian is evaluated in canonial, perturbed action - angle form for several stellarator vacuum field configurations. This form for the magnetic field permits relatively fast studies of details of the magnetic structure. In particular, one can find the magnetic islands through out a volume of interest by performing only a few, relatively short, field line integrations.

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CROSS MAGNETIC FIELD TRANSPORT DUE TO LIKE PARTICLE COLLISIONS *

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Cross magnetic field transport is discussed for a pure electron plasma in which the Larmor radius is small compared to the Debye length (i.e., $r_L \ll \lambda_D$). The elementary step of the transport process is produced by the $\underset{\sim}{E} \times \underset{\sim}{B}$ drift of a particle guiding center which occurs during a collision, where $\underset{\sim}{E}$ is the Coulomb interaction field. A guiding center analysis of the collision is appropriate for impact parameters which are much larger than the Larmor radius. Previous discussions of like particle transport focussed on collisions for which the impact parameter is less than the Larmor radius, and, for such collisions, the step in the guiding center is produced by scattering of the particle velocity vector. A calculation of the $\underset{\sim}{E} \times \underset{\sim}{B}$ transport, that is, of the transport due to large impact parameter collisions, yields a particle flux which exceeds that obtained previously by the factor $(\lambda_D/r_L)^2 \gg 1$.

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Lower Hybrid Wave Propagation in a Stochastic Plasma Background

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ABSTRACT

Several recent papers[1,2] have treated the effect of density fluctuations on lower hybrid waves in fusion plasmas. Assuming an electrostatic cold-plasma approximation the governing equation for the wave potential was shown to be intractable and consequently a wave transport approach was used to compute the transmitted and scattered lower hybrid wave intensity. We have chosen to remain with the original system of equations written in cylindrical geometry and have invoked the rather strict (and admittedly unrealistic) assumption that the density fluctuations are isotropic in the radial coordinate. The full wave equation can thus be transformed into a one-dimensional stochastic differential equation (SDE). A variety of techniques has been used to extract results from the SDE including first order smoothing which was investigated earlier by Sen[3]. The smoothing approach yields information pertaining to wave coherence only. Consequently, a calculation of the transmitted and reflected wave intensity is carried out following Papanicolau[4] using results due to Khasminskii[5]. Results to date and the applicability of the methods to realistic plasma wave propagation will be discussed.

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Adiabatic Limit in an Oscillating Doublet

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ABSTRACT

The configuration is a resistive doublet. The excitation is a sinusoidally varying boundary condition which is followed to a steady state. We are investigating the breaking and reconnecting of field lines in the adiabatic limit using an alternating dimension model. The adiabatic limit is given by $\omega\tau_s$ approaching infinity where ω is the frequency of ocsillation and τ_s the skin time. In the linear excitation range the flux transfer across the separatrix γ_ψ is a function of the product $\omega\tau_s$. However, in the nonlinear range γ_ψ is a function of ω and τ_s separately. In the adiabatic limit, the flux transfer (line breaking) approaches a finite nonzero limit.

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Transport in Stellarators: Some Special Features*

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a) Pinch Effect

Toroidal drift in the presence of an ambipolar field acts differently on electrons and ions and can lead to a change imbalance in the magnetic surface.(1) This leads to a poloidal electric field that can give an inward E x B drift (pinch) modifying transport by about 20%.

b) Collisionless Detrapping of Ions.

In classical stellarators the helical well depth varies with radius leading to collisionless trapping.(2) However, even a small amount of pitch angle scattering prevents collisionless retrapping and leads to an important correction to ion transport.

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Maximum Entropy and Direct Fourier Spectral Observations of Fluctuations in Turbulent Simulation Plasma

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We consider the general problem of classifying fluctuations in a simulation plasma as *coherent*, *e.g.*, waves or modes, or *incoherent*, *e.g.*, clumps or holes. This problem occurs in a turbulent plasma because plasma normal modes can be easily excited. For example, long-lived plasma oscillations at phase speeds greater than the thermal velocity can mask localized phase space fluctuations at phase velocities less than the thermal speed. Conventional diagnostics, such as the electric field spectrum $E_k(t)^2$ where k is the wavenumber, will not distinguish these two cases since a resolution of *phase velocity* (ω/k where ω is the frequency) is called for. We solve this problem by computing the power spectral density $S(k, \omega)$ from potential fluctuations $\delta\phi(x, t) = \phi(x, t) - \frac{1}{L}\int_0^L \phi(x, t)\,dx$ by four distinct methods described below. We will illustrate $S(k, \omega)$ in two idealized problems: (A) a one-dimensional, linearly stable electrostatic ion-electron plasma in which holes coexist with thermal plasma oscillations and ion acoustic waves[1]; (B) a hybrid 1-$\frac{2}{2}$ dimensional ion-electron plasma with uniform magnetic field in which ion cyclotron waves can coexist with non-wave-like fluctuations[2].

After spatial Fourier analysis to separate wavenumbers k, the normalized power spectrum $S(k, \omega)$ is computed from a signal $\phi(k, t)$ that is assumed to be band-limited, continuous and known only in a finite time interval $[0, T]$. The power spectrum may be estimated in at least 4 ways from its N samples $\{\phi_i\}$ $(i = 0, \ldots, N-1)$ at uniform time interval Δt. There are two direct Fourier methods: (1) form the magnitude of the discrete fast Fourier transform of $\{\phi_i\}$ with appropriate boundary conditions; or (2) form the magnitude of the analytic Fourier transform of an optimal continuous approximation to $\phi(t)$. In maximum entropy methods, $S(\omega)$ is computed directly from the Fourier transform of the estimated autocorrelation function $C(n\Delta t)$ of $\{\phi_i\}$. After obtaining M values of the autocorrelation function $C(n\Delta t)$, further values can be estimated by extrapolating the apparent autocorrelations for $|n| \geq M$ in such a way that no prejudicial information is introduced. This corresponds to asserting that there is no variation ($\delta\eta = 0$) of (3) the signal entropy density $\eta = \int \ln S(\omega)\,d\omega$ or (4) the signal entropy $\eta = \int S(\omega) \ln S(\omega)\,d\omega$ with respect to the unknown autocorrelations, given the M estimated autocorrelations.

Spectral methods (1) and (3) are in common use, while we believe methods (2) and (4) are new to the MFE community. All four methods are compared. They agree in certain limits in estimating the spectrum of idealized, known signals, but differ in quality and accuracy for other limits which will be discussed. Techniques for identifying growth rates as well as oscillations will be described. Fast, efficient (and vectorized) numerical techniques for these four methods will also be described.

This work is supported by D.O.E., N.S.F. and O.N.R.

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FLR-CORRECTED COLLISION OPERATOR: AN ALTERNATIVE APPROACH TO SOLVING THE FOKKER-PLANCK EQUATION

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A new method for solving the Fokker-Planck equation is introduced. In its general form, the method proceeds as follows. The phase space variables z_i (i=1,2,...n) are replaced by new variables $\overline{z}_i$ (e.g. guiding center variables), with the relation $\overline{z}_i = z_i + \delta z_i$. The distribution function $f(z)$ is replaced by $\overline{f}(\overline{z})$ (e.g., the guiding center density), with the relation $\overline{f}(\overline{z})d^n\overline{z} = f(z)d^n z$. Using a procedure related to earlier work by Sturrock (1) and Newman (2) on the quasilinear equation, the Fokker-Planck equation

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial z_i}(\dot{z}_i f) = C(f)$$

is transformed into

$$\frac{\partial \overline{f}}{\partial t} + \frac{\partial}{\partial \overline{z}_i}(\dot{\overline{z}}_i \overline{f}) = C^*(\overline{f})$$

where $C^*(\overline{f})$, the FLR-corrected collision operator, is a power series in the δz_i. An application to transport caused by ion-neutral atom collisions will be presented; essentially all of the algebraic complexity of the standard approach (3) to this problem is eliminated by this method.

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Studies on D-T Alpha-Driven Instability in Tandem Mirror Reactor

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Fusion product alpha particles in tandem plasma have a loss-cone-type distribution and are susceptible to drive microinstabilities through the coupling with a wave. This work investigates the alpha-driven Alfven wave microinstability in the central cell of the tandem, which is modeled by a homogeneous uniform plasma. The physics and mechanism of wave-particle coupling is examined. A computational model is developed to calculate the alpha-driven growth rate and study various effects of the instability. The growth rate is computed for different values of the Alfvén wave frequency for evaluating the most unstable frequency range. A net growth rate is found by including the damping from the background plasma ions and electrons. A survey code is developed to locate the regions in reactor operating regimes where the wave is unstable. The alpha threshold fraction (defined as the alpha particle number density divided by the plasma ion number density at marginal stability) required for instability is also determined. Future work will study the effects of decrease of alpha plasma heating and kinetic pressure, and ash removal at the reactor system level.

LOW FREQUENCY STABILITY IN TANDEM MIRRORS*

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Previous work was shown that kinetic effects will stabilize all but the low wave number MHD modes in a tandem mirror,[1] and has determined β-limits set by the rigid perturbation,[2] for which the kinetic corrections vanish. Here we use a 1-D axial eigen-value equation, derived from the long-thin FLR Lagrangian of Newcomb,[3] to explore the remaining low perpendicular mode number perturbations, for which rotational drive and kinetic terms are both important. The calculation assumes a quadrupole vacuum field, and treats equilibria either in the low-β limit[4] with various p(ψ) dependence, or using the finite-β sharp boundary model of Pearlstein and Newcomb.[5] For this latter case, a self-consistent model for the kinetic terms will be discussed. Comparisons with some analytic limiting cases will be made, and stability boundaries for TMX-Upgrade and MFTF-B will be presented.

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ENERGY LIMITING AND TEMPORAL EVOLUTION OF HOT ELECTRONS IN TMX-U*

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For optimum operation of TMX-U, it is believed that the hot electron energy should be $\sim$50 keV. For higher energies, the MHD stability properties are not as favorable. The original scheme for limiting the energy was to keep the ECRH microwave fields confined to a small axial region by strong single-pass absorption; as the electrons become relativistic, their cyclotron resonance shifts out of this region thereby limiting the heating. We investigate the influence of a small, spatially constant "cavity" ECRH field which may be present in TMX-U. Calculations are performed using the multi-region Fokker-Planck and Monte Carlo codes. For times corresponding to the current TMX-U experiment (50-100 ms), the cavity field does not strongly influence the electron energy because the relativistic heating characteristics intersect the turning point resonance line in momentum space. For longer times, collisional pitch-angle scattering can allow electrons to move to outer characteristics which have higher energy limits. Conditions for which this process results in significantly higher steady state electron energy will be discussed.

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STABILIZATION OF BALLOONING MODES IN AXISYMMETRIC MIRROR BY HOT ELECTRON RINGS AND RF ELECTRIC FIELDS*

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The use of hot electron rings and r.f. ponderomotive pressure to stabilize ballooning modes in a symmetric mirror configuration is studied using an axial eigenmode equation based on a rigid ring model. Some simple estimates of the conditions necessary for stable operation are presented for parameters relevant to the STM experiment at TRW and to the design of a proposed axisymmetric mirror experiment (AXIM) at UCLA. For parameters such as mirror ratio R=3 and $L_h/L=0.1$ where L_h is the axial length of hot electron ring and L is the distance between mirror throats, it is found that the threshold value of the hot electron ring beta β_h to stabilize ballooning modes is approximately 14%. This threshold value of β_h increases with increasing mirror ratio, and decreases with the axial length of the annulus.

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Electrostatic Instabilities Associated with the Axial Shear of the Azimuthal E × B Rotation in Collisionless and Collisional Plasmas*

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In tandem mirror configurations the equilibrium electrostatic potential varies both radially and axially. The radial potential variation gives rise to an azimuthal E × B plasma rotation, while the axial potential variation causes the azimuthal rotation frequency to vary along a field line. Using a high mode number, collisionless theory, it was shown that this axial variation in the azimuthal rotation can lead to instability[1,2]. We extend this work in two ways: (a) we consider the stability of an m = 1 rigid mode in a long-thin, collisionless plasma; (b) we show that a similar mode exists in a collisional plasma ($\nu_i < \omega \backsim \omega_E < \nu_e$, where ω, ω_E, ν_i, and ν_e are the wave, E × B rotation, ion collision and electron collision frequencies respectively). In both cases, we use a model, two region, TMX-like equilibrium to derive stability criteria for the instability. In the collisional situation the collision operator is left arbitrary.

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The Dynamics of the Collisionless Tearing Mode*

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The dynamics of the collisionless tearing mode is presented for comparable ion and electron temperatures. The solution of Maxwell's equations and the integral equation arising from the quasi neutrality condition in the constant 'ψ' approximation is obtained. The solution exposes the physics associated with the transition from the unmagnetised ion response in the inner region (where $\omega > \kappa_{\parallel} V$ the) to the magnetised response at a distance comparable to the ion gyroradius from the rational surface. The mode is stable for typical plasma parameters in contrast to the results of Drake and Lee.[1] The stability boundaries are given and the range of validity examined.

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IDEAL MHD BALLOONING INSTABILITY AND SCALING LAW FOR CONFINEMENT

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Abstract

The confinement time for an ohmically heated, low-β, tokamak is well described by the scaling law $\tau \propto n$. This implies that β should increase linearly with additional auxiliary heating power. In fact the increase is much slower, and confinement deteriorates with increasing auxiliary heating. We examine the possibility that this deterioration is due to the localised onset of mhd ballooning instabilities, with confinement elsewhere continuing to follow the law established for ohmic discharges. We find that the overall effect of the ballooning instability is indeed gradual and the resultant confinement time corresponds to a scaling law in good agreement with that reported for auxiliary heated tokamaks.

UPPER-HYBRID AND CYCLOTRON RESONANCES IN THE PRESENCE OF AN AMBIPOLAR ELECTRIC FIELD*

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The role of ambipolar electric fields in the magnetic confinement of plasmas is presently being recognized as an important issue. In such systems the zero order particle orbits are determined by a combination of the magnetic force and the electric force. As a consequence, the familiar vacuum cyclotron frequency $\Omega_o \equiv qB_o/mc$ is modified by the self-consistent electric field, which is governed by the charge imbalance of the system. In order to explore the consequences of such an effect we have studied an extreme case, namely, a single species plasma, driven by an external RF source at frequency ω. The zero order properties are determined from a Vlasov equilibrium in which the electrostatic potential is determined self-consistently. An unusual feature in these plasmas is that in the limit of small ρ/L, where ρ is the cyclotron radius and L the scale length for the electric field variation, the single particle cyclotron resonance does not occur at $\omega = \Omega_o$, but instead at $\omega = \Omega_1 \equiv (\Omega_o{}^2 - \omega_p{}^2)^{1/2}$, where ω_p is the local plasma frequency. Simultaneously, the cold plasma resonance, which for neutral plasmas occurs at the upper hybrid frequency, $(\Omega_o{}^2 + \omega_p{}^2)^{1/2}$, now appears at $(\Omega_1{}^2+\omega_p{}^2)^{1/2} = \Omega_o$. In other words, the usual roles of collective resonance and single particle resonance are, in a sense, reversed. A linear kinetic analysis is developed to investigate the propagation properties and absorption mechanisms of waves in the neighborhood of the collective resonance, $(\omega = \Omega_o)$.

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COLLECTIVE ENHANCEMENT OF RADIAL TRANSPORT*

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For a rotating plasma column in an axial magnetic field, we find that radial transport produced by field asymmetries may be enhanced by a collective resonance. This effect is demonstrated experimentally on a confined electron plasma column with applied electrostatic asymmetries. The pure electron plasma has a lifetime exceeding 10^5 axial bounce times, thus making it particularly suitable for a controlled study of the radial transport enduced by applied nonaxisymmetric perturbations. The enhancement mechanism is quite general and may be applicable to a variety of rotating plasma systems. For the case of a tandem mirror, the central cell plasma rotates and the field asymmetries are the quadrupole fields associated with the end plugs. For certain operating conditions, a drift wave can have zero frequency in the laboratory frame and be driven secularly to large amplitude by the static field asymmetries. The large amplitude drift wave can then produce enhanced resonant particle transport[1,2].

* This material is based upon work supported by the DOE contract DEAT03-82ER53129.

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1984 SHERWOOD THEORY MEETING
Incline Village, Nevada; April 11-13, 1984

ENHANCEMENT OF THE REACTION RATE BY ICRF HEATING *

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We examine the effect of fast wave ICRF heating at the second harmonic of deuterium in a D-T plasma. A theoretical model based on a one-dimensional Fokker-Planck equation in the perpendicular direction with an RF diffusion term is developed. The quasilinear RF diffusion produces an anisotropic tail of the deuterium distribution function. The height of the plateau is determined by the RF power density and it extends to the maximum energy of the confined ions. Recent experimental results of second harmonic ICRF heating of hydrogen plasma on PLT are explained by this theory [1].

The distribution function is different from the Maxwellian one and its tail leads to a signficant enhancement of the reaction rate. For D-T plasma the result is:

$$\overline{\sigma v}_{RF} = 6.98 \times 10^{-13}\, T^{-1/2} \int_0^{v_{\perp max}} v_\perp\, dv_\perp \exp\left(-\int_0^{v_\perp} \frac{x\,dx}{1+\frac{K_0}{3}T^{3/2}x^5}\right) \cdot$$

$$\int_0^\infty \frac{dv_\parallel}{\sqrt{v_\parallel^2+v_\perp^2}} \exp\left[-\frac{v_\parallel^2}{2} - \frac{48.46}{\sqrt{T(v_\parallel^2+v_\perp^2)}}\right]$$

where all velocities are normalized to the deuterium thermal velocity and T is in kev. K_0 is given in practical units:

$$K_0 = 1.8 \times 10^{-3} \frac{P_x\left(\frac{KW}{cm^2}\right)}{B^2(T)n^{1/2}(10^{14})}\frac{R}{a}$$

Here P_x is the power flow, B is the toroidal magnetic field, n is the density and $R(a)$ are the major (minor) radius. $v_{\perp\, max}$ is the maximum velocity of the confined deuterium ions.

For $K_0 \to 0$ we recover the usual Maxwellian result $\overline{\sigma v}_M$. For any given T in the range of $10 \div 20$ kev $\overline{\sigma v}_{RF}$ is bigger than $\overline{\sigma v}_M$ by a factor of 4–10. This leads to a signficantly reduced $n\tau_E$ from the power balance. At the same time Q_{RF} = fusion power/RF power can be made greater than 5, which is acceptable for a driven reactor.

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ORAL PRESENTATION REQUESTED

SHERWOOD THEORY MEETING 1984

April 11 to 13

Stability of Drift Waves in Stellarator and Tokamak Geometries*

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Stellarators such as Wendelstein VII are almost shearless but yet reportedly have a low level of fluctuations. Tokamaks on the other hand have a large level of such fluctuations even though the magnetic field is strongly sheared. Electrostatic particle simulation techniques (guiding center electrons, full dynamic ions) in 2 1/2 dimensions and in slab geometry are used to study the stability of drift-waves on stellarator-like geometry and tokamak-type. Three types of stabilization mechanisms are explored: (i)the compensation of the diamagnetic drift by ∇B and curvature drift, (ii)likewise by the rf porderomotive pressure, (iii)the descrepancy between the mode rational surface and the drift surface. The configuration employed is: exponential density gradient with scalelength L_n in the bounded x-direction, periodic y direction, magnetic field tilted on the y-z plane such that $B_y = B_o \sin\theta\,(1 + x^2/L_B^2)$, $B_z = B_o \cos\theta\,(1 + x^2/L_B^2)$, tilt angle θ so that $k_\parallel = k_y \sin\theta$ (in shearless case θ is independent of x) and magnetic field gradient scalelength L_B. Runs with various L_B/L_n show complete stabilization of the universal mode for $L_B/L_n \lesssim 5$ (corresponding to $R/a \simeq 2 - 4$), in agreement with shooting code results, by election ∇B drift concellation of the diamagnetic drift V_{de}. Whether L_B/L_n can be increased to more realistic values in such a way and yet retain stability is so far inconclusive because of rapid modification of the background profile of simulation plasma. An rf induced poderomotive force can play a similar role to quench the V_{de}. Further, since particle drift surfaces can differ by as much as a/2 from the magnetic surfaces in stellarators, other runs were performed with either perpendicular diffusion or harmonic bounce motion added to electrons and with mode localization either through weak shear or a tanh profile. Rapid bounce motion wipes out the resonance effect and yields Bernstein wave-like dispersion.

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SHERWOOD THEORY MEETING 1984

April 11 to 13

Multiple Hamiltonian Structure of Fluid and Kinetic Theory*

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The most natural formulation of the equations of plasma physics as Hamiltonian systems involves the use of non-canonical variables.[1] The Hamiltonian form for the equations for a field $\underset{\sim}{\psi}(\underset{\sim}{x},t)$ is $\dot{\underset{\sim}{\psi}} = \{\underset{\sim}{\psi},H\}$, where $\{\ ,\ \}$ is the Poisson bracket operator and H is the energy functional. Typically the Poisson bracket is degenerate: there exist functionals, C_k, such that $\{C_k,F\} = 0$ for all functionals F. The C_k are therefore invariant, and are called Casimir invariants from the theory of Lie Algebras.

We have reformulated the equations of motion of a system with N-1 Casimir invariants in terms of a non-degenerate, multilinear bracket with N+1 slots; that is, the equations of motion can be written $\dot{\underset{\sim}{\psi}} = \{\psi,C_1,C_2,\ldots C_{N-1},H\}$ where the bracket is completely antisymmetric. Such a system has effectively N Hamiltonians--the distinction between Hamiltonian and Casimir invariant is artificial. We show that if the multi-bracket satisfies a generalized Jacobi Identity (multi-Jacobi) then any N-1 Functionals can be used as Casimir invariants to reduce the multi-bracket to an ordinary Poisson bracket.

The simplest example of this structure is the rigid rotor which has a non-degenerate 3-bracket. We obtain 3-brackets for the Vlasov-Poisson and fluid equations as well. The former appeared as part of a formulation for dissipative systems[2,3]. Reduced MHD, on the other hand, has two simple Casimir invariants[3] leading to a 4-bracket.

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COUPLING OF ICRF POWER FROM DIELECTRICALLY LOADED WAVEGUIDES TO PLASMAS

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Due to the severe heat and neutron loading in a fusion reactor, it is advantageous to use waveguides to launch RF waves for heating. In the ICRH frequency range, the waveguides will probably be dielectrically loaded to reduce their size. We have calculated the coupling of a finite rectangular dielectrically loaded waveguide to a plasma, using the TE mode to excite an ion cyclotron wave. The plasma is assumed to have a line as density gradient, and the fields inside and outside the waveguide are matched as in the usual Brambrilla theory of lower hybrid wave heating.[1] Closed form algebriac expressions are found for wave reflection back into the waveguide. Over 90% absorption can be achieved with a reasonably sized waveguide with water used as the dielectric.

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Study of Electron Transport Utilizing Results of the ECH Experiment on PDX*

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In the past year electron cyclotron heating (ECH) has been successfully demonstrated in experiments on T-10, Doublet III and PDX. In each experiment there was a significant increase in the electron temperature without degradation of confinement. Optimal utilization of ECH to achieve the various goals envisaged for this type of heating requires, however, a better understanding of electron transport. While ion transport, in a number of tokamaks, is experimentally found to be of the order of the neoclassical diffusion rate, electron transport is found to be anomalous, i.e., at least two to three orders of magnitude larger than would be predicted by neoclassical theory. We have approached the study of electron transport by assembling data from a predictive transport code, linked to a ray tracing code, and then comparing the computed results with experimental data. In particular, we examine whether a transport model for χ_e, which is applicable for the ohmic heated plasma, is also applicable for the ECH heated plasma. The transport model is determined by matching the evolution of the plasma conditions as predicted by, BALDUR - a one dimensional transport code, with those deduced from diagnostic data obtained during a PDX ohmic discharge. In order to model electron cyclotron energy deposition in the plasma, TORAY, a ray tracing code which computes ray paths and associated energy deposition in toroidal geometry, is linked with BALDUR. We use wave and plasma parameters consistent with those of the ECH heating experiments carried out in PDX, e.g., $\bar{n}_e \simeq 1$ to 2×10^{13} cm^{-3}, $T_{eo} = 1.2$ to 2.5 keV, $I_p = 250$ kA and $P_{ECH} = 80$ kW for 40 msec. In our study, we examine the sensitivity of the expected heating to variations in the model for χ_e, to changes in the location of the ECH resonance zone and to details of the antenna pattern. We focus our attention on how the central heating of the plasma is affected by each of these factors.

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A CONCEPTUAL DESIGN OF A RADIOACTIVITY-FREE ^{3}He FUEL PROCESSING STATION IN A d-^{3}He NEUTRON-LEAN FUSION POWER PLANT*

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It is well known that the mixture of equal parts of deuterium and ^{3}He is a very attractive fusion fuel [1-4]. Burning this mixture ($T_i \gtrsim 70$ keV) releases $\gtrsim$96% of the fusion energy in charged products. This fusion fuel becomes extremely attractive if one suppresses the d-d reactions by nuclear spin polarization [5]. The $n\tau$ requirement for self-sustainment is modest [1-4] ($n\tau \gtrsim 10^{15}$ sec/cm^3).

On the other hand, ^{3}He is very rare in nature [1]. The required quantities of ^{3}He have been proposed [5-7] to be generated from the standard d-d fuel cycle with or without a lithium blanket.

Using the d-d fuel cycle to breed ^{3}He produces tritium and neutrons, and leads to the activations of the reactor structure and components. The safety issues for this ^{3}He breeder are comparable to a "standard" d-t fusion reactor. Precautions must be taken with respect to activations, tritium handling, and accident consequences. Accordingly, this breeder is suggested to be remotely located [5].

There is one promising nuclear reaction that can produce ^{3}He without neutrons or radioactive byproducts: $p + {}^6Li \rightarrow {}^3He + {}^4He + 4.02$ MeV. This reaction has a pronounced resonance which occurs at a proton energy of $E_p = 1.7$ MeV. The reaction cross-section remains above 100 mb for $E_p \geq 0.75$ MeV, indicating that there will be a good chance for an energetic proton or ^{6}Li to react with a target plasma ($T_i \geq 50$ keV) before slowing down.

A d-^{3}He neutron-lean reactor, that uses ^{6}Li doping of the plasma to partially produce the ^{3}He fuel in-situ will be conceptually designed. The high energy proton (14.7 MeV) resulting from the d-^{3}He reaction will be utilized directly to produce ^{3}He during the slowing-down process.

The additional ^{3}He that is required will be produced on-site by a fuel processing station that will use one of the two following schemes. One scheme consists of an accelerated high energy proton neutral beam impinging on a ^{6}Li plasma target. The other scheme accelerates singly charged ^{6}Li to a hydrogen plasma target. Each of these schemes has technology and cost trade-offs that will be investigated.

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NUMERICAL MODELING OF POLOIDAL DIVERTORS*

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Numerical modeling of divertors has been very successful in predicting useful operating regimes for tokamaks [1], and in quantitatively interpreting experimental results [2]. Detailed interpretation of experiments and reliable predictions for the future near-reactor tokamaks require very accurate representation of geometry, and fast and reliable numerical algorithms for solving the model equations. An orthogonal mesh based on the magnetic field geometry is usually required for discretizing of the model equations, and efficient and accurate orthogonal mesh generating methods have been developed. Also, new methods for finding steady-state solutions to the plasma fluid equations are discussed together with their application to PDX and INTOR modeling. PDX, in particular, has been modeled in detail and a very good quantitative agreement found with the experimental results. The sensitivity of the results to neutral-wall interaction models are also addressed, and the possible consequences for other experiments are discussed.

*Work supported by U.S. DOE Contract No. DE-AC02-76-CH03073.

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Axisymmetric Stability and Control in Toroidal Devices*

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The resistive axisymmetric simulation code STARTUP has been improved and applied to a number of test and design problems. Recent improvements include 1) a new form of enhanced viscosity which acts mainly on the compressible flow field and 2) a new boundary treatment in which the computational boundary is magnetically transparent. A model problem consisting of an elliptic cross-section plasma stabilized by passive resistive metal plates is studied extensively. We verify that the growth rate of the residual resistive instability is proportional to the resistivity of the plates and independent of numerical parameters. Design applications of the code include (1) radial and vertical feedback control system for PBX, (2) vertical control of DCT, (3) adiabatic compression of high - beta Q = 1 TFTR plasma, and (4) translation and adiabatic compression of S-1 spheromak plasma. Some comparisons are made with the ideal MHD code PSEC.

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Hall Effects on Tearing Modes

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ABSTRACT

The effect of Hall current on a tearing mode is examined by using the linear visco-resistive MHD equations for a compressible cylindrical plasma with Tokamak scaling. The speed of the mode rotation depends on four parameters related to the value of Δ' and the gradients of temperature, pressure and density at the pertinent rational surface. The mode rotation is numerically calculated for various values of the parameters and the results are discussed with an emphasis on the sign of the mode rotation.

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STABILIZATION OF THE SPHEROMAK TILT INSTABILITY*

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The tilt instability[1] of spheromaks puts a severe constraint on their usefulness as a plasma confinement device for a fusion reactor. Specially shaped conducting walls are not able to suppress the instability unless allowed to come very close to the plasma. Two possible ways of suppressing this instability are presented. In the first,[2] two spheromaks of opposite parity are squeezed together and confined in an external magnetic cusp field provided by external coils. Because the index $(R/B_z)dB_z/dr$ of the external cusp magnetic field is everywhere positive stability to tilt and rigid shift modes is assured. In the second,[3] a single spheromak is stabilized by a ring of energetic ions. Employing the generalized energy principle of Sudan and Rosenbluth[4] it is possible to show that in a ring spheromak system in which the (ring current)/(spheromak azimuthal current) $= \varepsilon \ll 1$, stability is assured if

$$\delta W = \delta W_p + \frac{4\pi}{3} \int dr\, r^4\, n_b q |\Omega| \tilde{B}_r > 0, \qquad (1)$$

where the radial spheromak magnetic field $B_r = \tilde{B}_r \operatorname{Cos}\theta$, (r,θ,ϕ) are spherical coordinates, n_b, q and $|\Omega|$ are the beam density, particle charge and angular velocity, $\delta W_p = V(B_*^2/4\pi)[(\alpha/5) - \delta r/R]$ is the contribution from the spheromak current, $\alpha > 0$ is the oblateness of the spheromak caused by the ring current, δr is the distance of the separatrix from the wall, B_* is the magnetic field at infinity and V is the spheromak volume. The second term in (1) represents the work done by the torque exerted by the displaced field of the spheromak on the ring current. It is important to note this expression is positive for beam particles outside and negative inside the separatrix because it depends upon field line curvature. This means that the stabilizing beam particles in the low density regime outside the separatrix have long life times and thus a significant improvement in the Q of a reactor based on the ring-CT hybrid configuration is achieved.

*Work supported by U.S. DOE Contract No. DE-AC02-76ET53065.

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ELECTROSTATIC AND MAGNETOSTATIC TANDEM MIRROR EQUILIBRIA FROM REALISTIC PLASMA DISTRIBUTIONS*

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Over the years the modeling of mirror equilibria has advanced to produce more accurate and realistic configurations. Modeling in 3D, precision coil field calculations, using pressures depending both on B and ψ, removing the long-thin approximation, inclusion of electrostatic effects, and many numerical innovations are among the features that are incorporated in some current equilibrium calculations. A weak aspect of these contemporary equilibria is that the pressure models used are very crude. Simple factored forms such as $P_\perp (B, \phi, \psi) = \hat{P}_\perp(B) F(\phi) w (\psi)$ have been used. Important species - such as sloshing ions - cannot be represented by such a separated form. Recently, pressure functions of the form $P_\perp (B, \phi, \psi,) = \tilde{P}_\perp (B, \phi) w (\psi)$ have been derived from analytic plasma distribution functions.[1] Furthermore they give a reasonable fit to known properties of sloshing ions and other species known to persist in tandem mirrors. Inclusion of these new models in the tandem mirror equilibrium codes ESTEQ and VEPEC is allowing us to compute more realistic configurations, particularly of the TMX-Upgrade experiment.

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*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

ROTATION AND IMPURITY FLOW REVERSAL IN TOKAMAK PLASMAS WITH NEUTRAL BEAM INJECTION*

by

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We have extended our previous collisional regime theory [1] for rotation and impurity transport in a tokamak plasma with NBI and strong rotation ($v_\phi \sim v_{th}$) to the plateau regime, which accomodates the important case of the main ion species being nearly collisionless and the impurity species being collisional - the mixed regime. This extension required a kinetic theory solution for the unaveraged as well as the averaged parallel viscous force $B.\nabla.\Pi$ with large rotation velocities and the incorporation of this viscous force into the fluid formalism. We allow for anomalous radial, viscous transfer of toroidal momentum, as indicated by experimental data [2,3]. The theory provides a self-consistent formalism for calculating toroidal and poloidal rotation velocities, the radial particle fluxes, the radial electric field and the poloidal variation of the impurity density over the flux surface.

The theory has been applied to interpret impurity injection experiments in ISX-B [3] and PLT [4]. We find a good correlation between the predicted impurity fluxes and the experimental observation of enhanced inward impurity fluxes with counter-injection and reduced inward or, for sufficiently large injected power, reversed (outward) impurity fluxes with coinjection.

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*For presentation at Sherwood Theory Conference April, 1984.

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PARAXIAL PROPAGATION APPROXIMATION FOR FAST MAGNETOSONIC WAVES IN TOKAMAK PLASMAS*

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A new approach to determine the power flow associated with the fast magnetosonic wave in tokamak plasmas has been developed using the paraxial approximation[1] of the wave equation in the plasma region between the fast wave cutoff at the edge and the mode conversion layer in the core. By solving for the wave amplitude directly, this approach provides a more accurate representation for the wave fields than can be obtained with ray tracing techniques because wave interference and diffractive effects are naturally included. These effects are ignored by ray tracing solutions. Moreover, statistical inaccuracies associated with the discretization procedures of ray tracing are avoided. Analytic expressions for the fast wave electric field in this region have been obtained using appropriate approximations to the full wave equation in the cold plasma limit. In the weak focussing region, where refraction of the wave is dominated by radial gradients in the equilibrium, the fields have been obtained from a paraxial approximation of the wave equation. In the strong focussing region, this solution is connected to a 1-D solution of the full wave equation in a homogeneous plasma to treat the convergence of the wave onto a focal spot on the mode conversion layer. A comparison between these approximate solutions and exact numerical solutions will be presented.

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FORMATION STUDIES FOR THE NEW MARYLAND SPHEROMAK (MS)*

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The formation phase of the new Maryland Spheromak is studied using a two dimensional, one fluid code. The code, which has ion viscosity, resistivity, parallel electron thermal conduction, perpendicular ion thermal conduction, and radiation, is a modified version of the code used by Lui et al.[1] In this new formation scheme the bias coils are located outside metal walls while the reversal coil is located inside the plasma chamber. The toroidal field is produced by currents through z-discharge electrodes located at the top and bottom ends of the chamber. A systematic study will be presented on the effect of varying the voltages, time scales, and phasing of the I_z and reversal coil banks. Sensitivity to radiation models and anomalous transport is also studied. It is found that the spheromak forms when the toroidal current due to reconnection at the X point on the midplane becomes large enough to form an O point and two X points which eventually reconnect. The toroidal current due to reconnection and the subsequent compression leads to substantial heating. The I_z current produces the toroidal field by a combination of differential rotation (dynamo) and magnetic compression. This field helps in producing the necessary force balance to form a low density large spheromak. Because of the constraints of force balance, optimal matching of voltages and phase of the banks is necessary.

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*Work supported by DOE.

SINGULAR BEHAVIOR OF THREE-DIMENSIONAL TOROIDAL EQUILIBRIA*

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Recently there has been growing interest in calculating three-dimensional toroidal MHD equilibria. This paper represents a continuation of our previous work.[1] We assume that magnetic field lines lie on smooth, nested, toroidal surfaces. It is extraordinarily unlikely that a given magnetic field configuration will have such regular magnetic fields. The result of the present work is that current sheets are ubiquitous among equilibrium magnetic fields that satisfy arbitrary boundary conditions, and have nested flux surfaces. That is, there are almost always places where the magnetic field strength is continuous, but its direction is discontinuous. Our analytic approach is perturbative, and follows that of Rosenbluth *et al.*[2] We linearize around a solution of the equilibrium equations that is nonsingular. The solutions of these linearized equations are small except in the vicinity of the resonant surface at which they are singular. The present calculation differs from the tearing mode calculation only in the model of the singular layer.

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INVERSE MAPPING ALGORITHM FOR MOMENTS FORMULATION OF MHD EQUILIBRIA*

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Toroidal MHD equilibria calculated from moments expansions generate Fourier series in the poloidal and toroidal (in 3-D) angles, and a coupled set of differential equations in the radial coordinate for the expansion coefficients. Numerical solutions for the inverse equilibria $[R(\rho,\theta,\phi),\ Z(\rho,\theta,\phi)]$ are therefore continuous in the angle coordinates and discrete only in the radial coordinate, thus requiring interpolation only in the ρ coordinate. When ϕ is the real toroidal coordinate, the inverse $[\rho(R,Z),\ \theta(R,Z)]$ in either 2-D or 3-D is easily and efficiently calculated by the iterative scheme

$$\rho_{n+1} = \rho_n + [Z_\theta^n(R_n - R) - R_\theta^n(Z_n - Z)]/g_n$$

$$\theta_{n+1} = \theta_n - [Z_\rho^n(R_n - R) - R_\rho^n(Z_n - Z)]/g_n$$

where

$$g_n \equiv R_\theta^n Z_\rho^n - R_\rho^n Z_\theta^n$$

is the Jacobian of the transformation from (R,Z) to (ρ,θ), and subscripts ρ and θ designate derivatives with respect to those coordinates. Examples of using the scheme in tracking segmented chords through flux coordinate space will be given. The method is useful for interpretation of diagnostics on experiments and as a geometry package for neutral particle transport, RF ray tracing, etc. in noncircular and/or nonaxisymmetic plasmas.

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Analytic Moment Method Calculations of the Drift Wave Spectrum

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A derivation and approximate solution of renormalized model coupling equations describing the turbulent drift wave spectrum is presented. Arguments are given which indicate that a weak turbulence formulation of the spectrum equations fails for a system with negative dissipation, such as the drift wave problem. The failure of the weak turbulence theory is shown to be directly related to the linear instability of the triplet correlation function. The inadequacy of the weak turbulence theory is circumvented by utilizing a renormalized formulation of the spectrum equation. An analytic moment method is developed to approximate the solution of the nonlinear spectrum integral equations. The solution method employs first order trial functions to reduce the integral equations to algebraic equations in basic parameters describing the spectrum. The parameters are obtained by solving the nonlinear coupled algebraic equations, which is done in part numerically. Equations which determine the next order correction of the parameters are also presented. The analytic moment method is tested by approximately solving the spectrum equations for a model dissipation proposed and numerically studied by Waltz.[1] The agreement between our approximate analytic moment method solution and the numerical solution of Waltz is excellent, both quantitatively and qualitatively. The analytic moment method is finally applied to the spectrum equation with a renormalized electron dissipation in the NSA.[2] The saturation aptitude and large frequency width are found to be in rough agreement with experimental observations in tokamaks.

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"THEORY AND SIMULATION OF THE FISHBONE INSTABILITY"

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RESISTIVE FLUID TURBULENCE AND ENERGY CONFINEMENT

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Abstract

The invariance properties of the underlying equations under scale transformations provide information about plasma transport. By applying this argument to specific models, in which the magnetic configuration and the physical mechanism of transport are identified, this information can be sufficient to completely determine the transport coefficients in a turbulent plasma. In this way the electron energy transport due to resistive fluid turbulence is examined in Tokamak and Reverse Field Pinch configurations. The resulting confinement times have interesting implications for the performance of the two systems.

SHERWOOD THEORY MEETING 1984

April 11 to 13

Theory of Turbulent Processes in the Tokamak Edge*

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Recent measurements of turbulence in the edge region of tokamaks have provided data which depict both the nature of the fluctuations and associated anomalous transport as well as the mean temperature, density and electric field.[1,2] These latter indicate the existence of a mean radial electric field which can reverse sign in the edge region and implies diamagnetic rotation in the ion direction at the extreme edge and electron direction further in. Flow visualizations also suggest the presence of vortex-like motion in the region of the electric field null point.[2] In this paper we present a theory which describes the turbulence arising from two types of processes associated with typical edge density and temperature profiles and a radial electric field.

In the basic model, localization of the fluctuations is determined by the magnetic shear and is not strongly altered by the radial electric field. The instability is driven by the free energy associated with gradients in the density or temperature and the radial electric field introduces a doppler shift. For this limit we consider a collisional drift wave instability appropriate for isothermal electrons. The mode coupling equation is treated analytically, retaining both coherent and incoherent mode coupling contributions. The analytic formulas indicate that the spectrum is characterized by broad linewidths ($\Delta\omega_k/\omega_{*e} \sim 1$) with energy predominately in the small wavenumbers ($k_\perp\rho_s \sim 0.1$). Asymptotically, the spectrum decays as $k^{-17/6}$ and ω^{-2} for large wavenumber and frequency, in good agreement with observations. The fluctuation level scales as ρ_s/L_n with magnitudes of 30% for typical edge parameter values. The particle diffusion is Bohm-like in magnitude. It does not however, follow Bohm scaling, but goes as $D \sim n^{2/3}T_e^{1/6}$. These results are in qualitative agreement with experimental measurements.[1] For comparison we allow electron temperature fluctuations and present edge turbulence predictions based on a rippling mode model.

It is possible that the electric field shear plays a fundamental role in the instability process. In particular, data suggests that modes centered on the electric field null point arise and are driven unstable by the electric field shear in (possible) combination with pressure. The instability is essentially a Kelvin-Hemholtz instability. Growth rates for several possible configurations of pressure and electric field are obtained from a reduced MHD model. Saturation estimates obtained from consideration of the mixing of turbulent fields through the shear layer are presented. An attempt is made to integrate various considerations given in this paper and provide a unified picture of edge turbulence.

*Work supported by USDOE.

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Reduced Equations for Finite Beta Resistive Modes in Tokamak*

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A reduced set of resistive magnetohydrodynamics (MHD) equations is derived that is applicable to both high-beta and low-beta tokamaks to study the linear and nonlinear evolution of finite beta resistive modes. The equations eliminate the fast magnetosonic wave thus simplifying the numerical integration of resistive MHD. However, all effects relevant to the anlysis of tearing modes are retained. In particular, by performing a subsidiary ordering in η, the plasma resistivity, we recover the equations of Coppi, Greene and Johnson.

The reduced equations have been coded for the cylinder and torus by extending the initial value code HILO.[1] Comparisons between the reduced equations and other methods of integrating resistive MHD will be presented to show that the reduced equations do in fact give excellent quantitative results.

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3-D MHD STABILITY OF HIGH-BETA FREE-BOUNDARY PLASMAS WITH FINITE EDGE-PRESSURE-GRADIENT AND LIMITER STABILIZATION*

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Linear and nonlinear characteristics are studied for ideal and resistive external kink-tearing-ballooning modes in high-beta toroidal tokamak plasmas with varying pedestal pressure near the plasma edge and/or with stabilization due to a limiter. Nonlocal analyses with finite toroidal mode number n are used via HIB code[1] for $1 \leq n \leq 10$. When the pedestal value is small,[2] the mode spectrum peaks near $n = 1$ with monotonically decreasing growth rate in n, in which case the most unstable mode has a structure of basically ideal high-beta external kink mode. The nonlinear evolutions with several n numbers are often dominated by the fastest growing $n=1$ mode, exhibiting predominantly single frequency oscillations in Mirnov and soft x-ray probes. As the pedestal value increases,[3] the linear growth rate decreases for a fixed beta and the mode spectrum tends to broaden with the perturbation increasingly localized near the plasma edge resembling the edge relaxation phenomenon in an H-mode tokamak discharge. The broadened mode spectrum affects the nonlinear evolutions in that the possibility of the appearance of multi-frequency oscillations with more than one n number increases compared with the peaked mode spectrum case with a small pedestal value. The stabilizing effect of a limiter to high-beta MHD modes is examined in various cases: an axisymmetric toroidal limiter (similar to the line-tying in an H-mode diverted discharge), a poloidal limiter, and a general limiter which is in contact with the plasma in a finite toroidal and poloidal region. In the latter two types of limiter, a 3-D analysis is necessary even for a linear stability. Unlike a zero-beta cylindrical case with a line contact,[4] a high-beta toroidal case with finite area contact has different characteristics; among them is the substantial reduction in growth rate even with modest contact area. Optimum position and contact-area of a limiter are found through extensive parameter studies[5]; e.g., the optimum poloidal position is $\theta = \pi/4$ followed by $\theta = 0$ or $\pi/2$ and then by $\theta = 3\pi/4$ or π. A scheme to stabilize the high-beta external kink-tearing mode by means of a set of passive feedback coils behind a nonconducting ordinary limiter is also discussed.

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AN ULTIMATE BETA-LIMIT FOR MACROSCOPICALLY STABLE TOKAMAKS*

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An analytic approach to the ideal-MHD equilibrium and stability of large aspect ratio, fixed boundary tokamak configurations in which β is as high as a quantity of the order of unity, is presented. This analysis is of general nature, in the sense that it applies to exact solutions of the hydromagnetic toroidal equilibrium equation with no restrictions on the shapes of the magnetic surfaces or the plasma boundary. It is shown that, in the $\beta \sim 1$ regime of interest, the orderings $\beta_p \sim \varepsilon^{-4/3}$, $\beta_I \sim \varepsilon^{-5/3}$ must hold for any equilibrium, irrespective of its details. When the stability of these configurations against long wavelength modes is considered, it is found that they are unstable against a pressure driven perturbation whose radial amplitude is localized in the region of unfavorable magnetic curvature, but vanishes at the outer side of the torus midplane. This instability sets an unavoidable β-limit for ideal-MHD stable configurations and puts an upper bound on the "second" domain of stability. However, given the constraints on the mode eigenfunction, it is expected to have a rather high β-threshold thus allowing for a sizable "second stability region" in the finite-β regime characterized by $\beta \sim \varepsilon$, $\beta_p \sim \beta_I \sim \varepsilon^{-1}$.

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Numerical Evaluation of Collisional Trapped-Particle Modes in Tandem Mirrors*

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In a recent study of trapped particle modes in tandem mirrors[1], a dispersion relation, valid for arbitrary ratio of collision frequency ν to diamagnetic drift frequency ω_*, was derived. However, tractable analytic expressions for real frequencies and growth rates are obtainable only in certain asymptotic regimes of ν/ω_* and only when other simplifiying assumptions (e.g., anchor curvature much larger than that required for marginal flute-average stability) are made. Here we evaluate the dispersion relation numerically, allowing us to track roots between the asymptotic limits and to explore a wider range of parameters. In particular, it is seen that when charge overshoot produces two stable collisionless trapped-particle modes, the lower-frequency root, which is destabilized by collisions, tracks smoothly into an electron drift wave as the collision frequency is increased, with maximum growth rate at $\nu R/\omega_* \sim 1$. The higher-frequency root is damped by collisions, becoming increasingly so as ν/ω_* is increased. Additionally, two modes which are flute-like at high collisionality are followed into the collisionless regime. Extension to include energy scatter[2] is also discussed.

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ANALYSIS AND SIMULATION OF THE TRAPPED PARTICLE MODE IN TANDEM MIRRORS*

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Two-region square well models are used to obtain results (both analysis and simulation agree in all respects) for two distinct problems.

1. The passing density required for marginal stability, n_{pm}, can be considerably larger than n_{pc}, the value usually quoted and calculated assuming the mode isolates to the center cell. The ratio n_{pm}/n_{pc} depends on the strength of the flute stability of the system, xfc = ω_f^2/γ_c^2 where ω_f is the real frequency of the stable MHD flute mode, and γ_c is the flute growth rate of the center cell alone. The ratio $n_{pm}/n_{pc} \rightarrow 1$ only at very large xfc. for example, with xfc = 0.5 we calculate n_{pm}/n_{pc} = 4.8, for xfc = 1.0 we have n_{pm}/n_{pc} = 2.7, and for xfc = 3.0 we have n_{pm}/n_{pc} = 1.5. This result should affect design criteria (e.g. MFTF-B) that depend on the stable value of n_p.

2. Results for the velocity shear trapped particle mode, driven by $\omega_E^{(z)}$, show a different behavior in a number of respects compared to those quoted in the literature[1]-- a dispersion relation for a flute mode identical to that for the mhd shear mode, independent of n_p. In contrast, we find larger growth rate for larger n_p, stability for n_p below some critical value, and in general we do not obtain a flute mode. Also, the mhd mode has a growth rate proportional to the azimuthal mode number, yet another feature not observed in our results.

The observed n_p behavior is opposite to that for the usual trapped particle mode, which is stable for higher n_p. This suggests that there may be some version of the trapped particle mode unstable over a much wider range of n_p that has heretofore been calculated. The dependence on n_p also suggests that this shear mode could be more important for highly collisional plasmas, in particular in TMX-U.

Extensions of the simulation model to include collisions, to nonsquare-well models, and to coupled r-z models will be discussed.

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FEEDBACK CONTROL OF TRAPPED PARTICLE MODES IN TANDEM MIRRORS*

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Feedback control of trapped particle modes via a modulated neutral beam has been proposed in a different context[1]. However, it is technologically complex and difficult. A technologically simpler approach is the axial feedback using end plates in a mirror machine[2]. In a well-plugged tandem mirror, the sheath resistance at the end plate is enormous, thus making the coupling to the core plasma by this method nearly impossible. All tandem mirrors now have cooler, lower-density halo plasma. Halo plasmas of $T_e \sim 50$ eV and $N \sim 10^{13} cm^{-3}$ will be maintained in MFTF-B and reactor type tandem mirrors to protect the hot central core[3] Segmented annular end plates in contact with the halo plasma at the end of the machine, are proposed as feedback suppressors. The sheath resistance is very small and excellent coupling to the core plasma is possible. It is shown that very modest feedback gain can stabilize m=1, collisionless trapped particle mode, even in the complete absence of any passing ions in MFTF-B type tandem mirror.

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2P4

STABILIZATION OF RESISTIVE BALLOONING MODES BY ELECTRON THERMAL CONDUCTIVITY

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ABSTRACT

The linear stability of resistive ballooning modes (RBM) in a high temperature tokamak plasma is examined, taking account of the effect of temperature gradients and finite parallel electron thermal conductivity. We have obtained the solutions of a fourth order differential equation from a variational formulation. We have shown that the coupling of parallel thermal conductivity and temperature gradient can have a strong stabilizing influence on high mode number RBM which classically have growth rates proportional to $\eta^{1/3}$ and $\eta^{3/5}$. The physical origin of the stabilization is related to additional pressure driven currents that arise close to the mode rational surfaces as a result of this coupling. Using the scaling argument, we are able to deduce a critical β, the ratio of thermal to magnetic pressures and we find complete stabilization of RBM at high temperatures for typical β in the range $\frac{\epsilon^2}{q^2} < \beta < \frac{\epsilon}{4q^2}$ where ϵ and q are the inverse aspect ratio and safety factors, respectively. Since these modes are suspected to control the electron heat loss from tokamaks, these results could have some relevance to present and future finite β tokamaks.

Thermal Barrier Pumping and Alpha Control using Low Energy Neutral Beams in a TARA Reactor*

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We consider a tandem mirror reactor based on TARA type end plugs [1] with similar central cell parameters as MARS. The central cell is bounded by axisymmetric mirror plugs which contain the thermal barrier and ion plugging potential. Beyond the plugs a short open transition maps the flux tube into ECRH heated low field quadrupole anchors.

A controlled radial diffusion may be applied in the central cell so that ions (D, T, and alphas) and possibly electrons primarily leave radially. Pumping of the thermal barrier may then be obtained by expelling ions and alphas into the central cell. Good neutral beam access into the thermal barrier region of the plugs introduces the possibility of neutral beam pumping. This option is desirable because the physics is conceptually simple and no difficult extrapolation of technology is required.

Using a variational technique and assuming a square well model of the thermal barrier [2], we evaluate a pumping scheme in which only shallowly trapped D-T is strongly pumped by low energy neutral beams. The necessary pumping rate is found to increase by a factor of the density ratio squared; $\left(\frac{N_{tL} + N_{tH}}{N_{tL}}\right)^2$. ($N_{tL}$ and N_{tH} are the density of the trapped particles in the pumped region and the unpumped region, respectively). A one dimension model is used to estimate this density ratio. The resulting power requirements are found to be acceptable. Low energy neutral beams may also be used for thermal barrier alpha removal [3]. We evaluate a scheme in which shallowly trapped alphas are returned into the central cell where they can diffuse out radially.

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SHERWOOD THEORY MEETING 1984

April 11 to 13

Evidence of Discrete Alfvén Waves in a Plasma Column

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Discrete or global Alfvén eigenmodes (GAE)[1] have been observed in a plasma column using a 3-dimensional particle MHD code[2]. The code was first run with a thermal level of fluctuations (linear case) to pinpoint the spatial structure and frequency of the modes. Analysis of the simulation data by interferogram techniques reveals a number of GAE's with different m (poloidal) and n (toroidal) mode numbers and radial locations. They all have the following predicted properties: helical structure with helicity opposite to the kink modes, broad spatial structure, frequency $\omega_{mn} < (k_{\parallel} C_A)^{min}_{mn}$, narrow symmetric spectral width $\Delta\omega/\omega \lesssim 2\%$. Next, selected modes were externally driven (nonlinear case) by antennas close to the wall inside the column. We observe deeper penetration of the external perturbation for modes localized inside the column, which is good for heating, but better coupling for modes localized more on the surface, with a larger increase of fluid kinetic energy. Saturation of the modes occurs after 10-20 wave periods with some toroidal mode coupling and considerable asymmetric broadening of the resonance (for the modes considered) up to $\Delta\omega/\omega \lesssim 15\%$ for perturbation levels of $\tilde{b}/B_o \approx 10\%$.

*Work is supported by USDOE.

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MONTE CARLO CALCULATIONS FOR THE ISX PUMPED LIMITER*

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This paper presents the results of Monte Carlo simulations of the neutral particle transport inside the ISX pumped limiters[1] using the computer code DEGAS.[2] In particular, densities and temperatures inside the limiter chamber are calculated for a variety of plasma edge conditions and found to be quite similar to those measured. The drop in pressure between the pumped and unpumped cases is not as large as measured, but could be explained by the differences in edge conditions for the two cases. There appears to be little plasma plugging, and the confinement time of a particle in the chamber is relatively short.

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*Work supported by the U.S. Department of Energy.

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Neoclassical Tokamak Transport with Toroidal Flow

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ABSTRACT

As Tokamak experiments become larger, cleaner, and hotter, more precise calculations and modelling of particle and energy transport become desirable. We describe here such a model along with numerical calculations intended to represent neoclassical Tokamak transport. We employ the equations of dissipative magnetohydrodynamics with sources and in axisymmetry. We include tensor viscous effects in the equations of momentum and energy conservation, anisotropic heat flow and electrical conductivity in the energy equation, and anisotropic electrical conductivity and Hall effect in Ohm's law. We start from the Braginskii forms of the viscous stress tensor, anisotropic heat flow vector and anisotropic conductivity tensor. In order to represent the neoclassical forms we include multiplicative correction factors to the standard forms. The various transport coefficients are of greatly disparate magnitude. The parameter $\varepsilon = (\omega_c \tau)^{-1}$ measures the relative smallness of various forms and is in the range 10^{-3}-10^{-6}. Such values are so small compared with inverse aspect ratio, plasma beta, or B_p/B that we take all the latter quantities of order one in ε, and we may then take the neoclassical corrections to Braginskii transport all to be factors of order one. We now employ a systematic expansion in ε.

In lowest order in ε the steady state solution is given by a Grad-Shafranov equation for the magnetic flux functions $\psi(r,z)$, but with the pressure a specified function of r and z, and a purely toroidal flow whose angular velocity is a function of flux alone, as is the temperature. In first order in ε we find that a poloidal flow is required to achieve momentum balance. This flow lies in a flux surface and does not contribute directly to particle or energy outflow. No particle or energy outflow occur in this order. A generalized linear Grad-Shafranov equation determines the first order perturbed magnetic flux function. Otherwise all first order quantities are determined by integrals on flux surfaces. These integrals contain automatically the Pfirsch-Schlüter corrections. In second order in ε we admit particle, momentum, energy, and current sources: we also allow the lowest order equilibrium to evolve on this time scale. We solve the equations only to the extent necessary to find the slow temporal evolution of the lowest order equilibrium.

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Bounce-Averaged Monte-Carlo Calculations of Ripple Transport.*

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Analytic theories of transport due to ripple-trapped particles employ the 'longitudinal invariant', $J = \oint V_{\parallel} d\ell$, which is approximately constant along the drift orbit, to describe particle trajectories. A Monte-Carlo calculation is being developed which finds the bounce-average position of a ripple-trapped particle after a step in poloidal angle iteratively, conserving J, and which scatters such particles using a bounce-averaged collision operator. The average radius is found using a first estimate of the form

$$r = r_o + \frac{Vd}{\omega_\theta} \cos\theta$$

where V_d is the vertical drift velocity and ω_θ is the poloidal drift frequency due to the radial electric field. It is then calculated to high accuracy iteratively using

$$r_n = r_{n-1} + (J_{n-1} - J_{real})\,(r_{n-1} - r_{n-2})/(J_{n-1} - J_{n-2}).$$

Typically, four or five iterations give 7 figure accuracy. When the pitch-angle variable k^2 (which is zero for deeply trapped particles and 1 for barely-trapped particles) reaches 1, it is necessary to iterate in r and θ, to find the precise detrapping point. A total of about 20 iterations is necessary to obtain similar accuracy in this case. When particles detrap, in a collision or collisionlessly, they become toroidally trapped or passing when a more standard collision operator is employed. Superthermal particles in a plasma with reactor-relevant parameters require ≈ 1/2 s on the MFECC CDC 7600, per Coulomb collision time, τ_c, so e.g. 500 particles, followed for 10 τ_c (and for the particles in question $\tau_c \approx$ 1s) would require 50 minutes of running time, (priority 0.1 gives very rapid turnover, however.) It is hoped that such a calculation will aid understanding of existing analytic theories and Monte-Carlo simulations of transport, since a.) the present calculation is faster than a guiding-center code and b.) it can be made to closely correspond to the assumptions of analytic theory, or improve on analytic theory, to test existing results.

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Simulation of Injected Impurities on TEXT*

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The trace impurity injection experiments[1] on TEXT have been simulated by numerically solving the time dependent radial transport equations which describe the ionization, recombination and transport of several ionization states of an impurity. In the TEXT experiment, a trace amount of scandium was injected during the current plateau and the resulting radial profiles and chord averaged brightenss Sc^{+10}, Sc^{+12}, Sc^{+15} and Sc^{+16} were measured. In the simulation, the ionization and recombination rates were calculated using the measured electron temperature and density profiles which were found to remain constant during the experiment. The particle flux was assumed to be of the form:

$$\Gamma_z = -D\frac{\partial n_z}{\partial r} - \left(\frac{r}{a}\right) V n_z$$

The equations are solved for the time evolution of Sc^{+11} to Sc^{+19}. The evolution of Sc^{+10} is adjusted to follow the experiment and used as a driving function in the calculation. The values of D and V were adjusted to give the best fit to the rise and fall times of the chord averaged brightness and to the radial position of the peak and width of each of the measured profiles. Initial comparisons with experiment in which D and V are assumed to be constant over space, time and charge show that $D \approx 10^4 cm^2/sec$ and $V \approx 3 \times 10^3 cm/sec$.

With the impurities in the Pfirsch-Schlüter regime, the diffusion coefficient is expected[2] to be independent of Z while V should depend linearly on Z. Therefore, a particle flux of the form:

$$\Gamma_z = -\left(D\frac{\partial n_z}{\partial r} + ZD\left(\frac{1}{2} + \frac{1}{Z}\right)\left(\frac{T_i'}{T_i} - \frac{n_i'}{n_i}\right)\right)$$

may be expected to give a better fit to the data. Results of this comparsion will be presented.

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SHERWOOD THEORY MEETING 1984

April 11 to 13

DESTABILIZATION OF IDEAL BALLOONING MODES BY ENERGETIC TRAPPED PARTICLES

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A recent theoretical analysis of magnetohydrodynamic ballooning found that a very high energy trapped particle species may enhance the stability of tokamak plasmas.[1] At moderate energies, however, the condition that the magnetic precessional drift frequency of these particles be larger than the typical MHD growth rate is no longer valid. In this case, the MHD mode is found to acquire a real frequency which is close to the trapped particle precessional frequency, as is also the situation for the internal kink mode that explains fishbone oscillations.[2] Here we investigate how the coupling of the trapped particle precessional mode with the ideal ballooning mode lowers the predicted critical beta limit. This effect may furnish a potential explanation for the observed degradation of confinement in beam-heated tokamaks.

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Destabilization of Ballooning-Precessional Mode in Hot-Electron Plasmas*

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It has recently been shown that under reactor conditions, where the hot electron curvature-drift frequency is expected to be small compared to the core-plasma ion gyrofrequency, coupling of interchange and negative-energy precessional modes forms an unstable entity over a large region of parameter space.[1-3] The present analytical work extends these earlier studies by admitting outgoing-wave boundary conditions, leading to dimunition of the region of stable operation. Possible modifications due to the non-local dependence of the parallel component of the perturbed magnetic field on the perturbed electrostatic potential are considered.

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*Work supported by U.S. Department of Energy contract DE-AC03-76-ET53057.

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SHERWOOD THEORY MEETING 1984

April 11 to 13

Nonlinear Interaction of Tearing Modes and Dynamo in the Reversed Field Pinch

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The magnetic fluctuations and dynamo activity observed in the RFP are thought to be a consequence of the nonlinear interaction and evolution of m=1 tearing modes. Recently,[1] theoretical and computational investigations have indicated that a likely saturation mechanism for multiple helicity m=1 turbulence is the coupling of energy (first) to stable, nonlinearly driven m=2 islands, and ultimately to resistive dissipation at small scales. The m=1 fluctuation saturation level was obtained and used to compute the turbulent electric field $\langle \hat{V} \times \hat{B} \rangle$.

In this abstract, extensions of and additions to previous work are described.

(i)The high temperature regime where $\omega_{*e} > \gamma_{m=1}$ ($\omega_{*e} \equiv$ electron diamagnetic frequency, $\gamma_{m=1} \equiv$ m=1 growth rate) is considered. Because of diamagnetic rotation, the nonlinear coupling of the m=2 to the m=1 (which remains purely growing) is weakened. Hence, at saturation $\delta B/B_o \sim |\omega_{*e}\tau_A|$, rather than $\delta B/B_o \sim \gamma_{m=1}\tau_A$ as in pure MHD case. It is worthwhile to note that this result is <u>not</u> a consequence of the change in the linear growth rate of the m=1. A renormalized theory will be presented and the possibility of nonlinear (m=1 mode) frequency shifts discussed.

(ii)In previous work, the increasing stability of the larger m nonlinearly driven modes ($|\Delta'_{m_2}| > |\Delta'_{m_1}|$, for $m_2 > m_1$) appeared only in the coupling coefficients of the energy mode coupling equations, while the current gradient term $\langle \hat{\phi} \nabla_y \hat{\psi} \rangle \partial \langle J \rangle / \partial r$ was neglected (for m>1). A quasilinear estimate reveals this effect, associated with torsion of the current profile by the nonlinearly driven (i.e., stable) m>1 fluctuations, to be a moderately strong sink of fluctuation energy. The fluctuation energy decrease is equal to an increase of energy of the average magnetic field configuration. Hence, expenditure of fluctuation energy required to drive $\Delta'<0$ modes is now accounted for. Inclusion of this effect results in a large m spectrum decaying (as m increases) more rapidly than that previously derived. The new result is more consistent with computational results and experimental observations.

(iii)An alternative formulation of the dynamo calculation is given.

[1]1983 APS-DPP papers 4W11,12; 7A4; 8U5.

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ELECTRON MICROINSTABILITIES IN RELATIVISTIC MIRROR PLASMAS*

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Relativistic treatment of instabilities in the electron cyclotron frequency range is necessary to model plasmas in devices like the Tandem Mirror Experiment Upgrade (TMX-U) at Lawrence Livermore National Laboratory. We write the linear dispersion relation in terms of energy and pitch-angle variables. We model the hot electrons with a distribution that is separable in these variables and piecewise constant in the pitch-angle variable. Then, both for parallel ($k_\perp = 0$) and perpendicular ($k_\parallel = 0$) propagation, we can analytically perform the pitch-angle integration that appears in the dispersion relation.

For $k_\perp = 0$, numerical results indicate that whistler instability has a frequency ($\omega < 0.6\ \Omega$, where Ω is the rest-mass cyclotron frequency) below that of the nonthermal cyclotron emission observed in TMX-U through January 1984. That emission may be due to the cyclotron-maser instability (CMI). We find that CMI is sensitive to the shape of the distribution F(E) of hot-electron energies. For example, depending on F(E), cold electrons stabilize CMI for $n_{cold}/n_{hot} \ll 1$ or $\gg 1$. Available numerical results for $k_\parallel = 0$ will be shown.

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FLARE: A 3-D LINEARIZED COMPACT TORUS STABILITY CODE

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In the parameter regime corresponding to reactor operation of compact toroids, the combination of compact geometry, low aspect ratio, and high β produces a plasma in which ion gyroradius is comparable to the plasma scale length. The stability of such plasmas can be affected by ion kinetic effects.

We have developed a 3-D linearized stability code, FLARE (Finite LArmor Radius Effects), to study ion kinetic effects on the low-frequency stability of compact toroids (spheromak, field-reversed Θ-pinches, and field-reversed mirrors). The code analyzes hybrid (particle ion, fluid electron) axisymmetric equilibria by numerically integrating the perturbed linearized plasma dynamic equations in time.

We will present normal mode tests of the code which confirm the dispersion of magneto-acoustic waves. We will also compare the results of FLARE for the stability of a spheromak equilibrium to those of the MHD eigenvalue code GATO, for a similar equilibrium in which ion kinetic effects are not expected to be important, as a verification of code performance.

We intend to use the code in understanding, both qualitatively and quantitatively, the departure from MHD stability theory due to finite Larmor radius effects in compact toroids. Such understanding will have great impact on the future of compact toroids as potential fusion reactors.

Study of Stellarator Devices by Expansion Techniques*

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Significant progress has been made in developing tools for design of stellarators and for interpretation of experimental results. Many of these advances result from application and improvement of expansion techniques.[1,2] The expansion has also given insight for analysis and interpretation of experimental results from Wendelstein VII-A.[3] Equilibrium and stability studies of Heliotron E using these stellarator expansion codes predict instabilities when the average β is greater than 1.1% to 1.5%, depending on the pressure distribution, in agreement with recent experimental results.[4] The unstable modes are due to plasma expansion in regions of unfavorable average magnetic field line curvature. They tend to be localized near the $q = 1$ surface. Introduction of an axisymmetric pusher coil on the outside of the plasma, together with a uniform vertical field, can distort the lowest-order magnetic surfaces into a backwards D and modify the equilibrium properties to provide stability. Introduction of this shaping technique on Heliotron E would interfere with the neutral beam injection system, but the approach could improve the stability properties of other stellarators such as Wendelstein VII-A. The stellarator expansion provides an easy way to test this type of system design and optimization. The equilibria produced by the codes can be used in conjunction with recently developed techniques[5,6] for studying the degree of surface disruption and island formation that the resonant fields could create.

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2P17

THE DISPERSION FUNCTIONAL FOR MULTIDIMENSIONAL EQUILIBRIA * AND ITS APPLICATION TO FIELD-REVERSED CONFIGURATIONS

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Numerical study of the linear stability of plasmas is very difficult when one or more of the plasma species is collisionless and the equilibrium is multidimensional, that is, characterized by two or more nonignorable spatial coordinates. The problem arises, for example, in evaluating kinetic stabilizing effects on the tilting mode in field-reversed configurations. We derive the Laplace transform of the perturbation distribution function for all classes of phase-space trajectories and use it to construct the dispersion functional for multidimensional equilibria. The dispersion functional is expressed in terms of a time autocorrelation function of the Laplace transform of the perturbation Hamiltonian without an assumption of stochastic or ergodic trajectories. The dispersion matrix that is used for stability computations is derived from the dispersion functional. An important feature of this form of the dispersion functional is that the orbit integrals in the elements of the dispersion matrix do not depend on the eigenfrequency ω. This means that the dispersion matrix can be obtained for different values of ω without recalculating the orbit integrals. No resonant denominators appear in this form of the dispersion functional. The same dispersion functional can be obtained formally by using Liouville eigenfunctions. That derivation is interesting because it depends on the existence of canonical variables that include the energy and its conjugate time variable. Except for the case of one nonignorable coordinate, the properties of such variables are surely pathological. For the case of the Vlasov-fluid model, we have transformed the dispersion functional in a way that is particularly appropriate for plasma stability computations. We present some numerical examples based on a field-reversed equilibrium that illustrate the desirable properties of this form of the dispersion functional.

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DIFFUSION IN THE QUANTUM STANDARD MAP WITH NOISE*

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The standard map,

$$x_{n+1} = x_n + p_{n+1}$$

$$p_{n+1} = p_n - \varepsilon \sin x_n$$

is a much studied Hamiltonian system displaying stochasticity and diffusion in the p coordinate for $\varepsilon \gtrsim 1$. The quantum standard map is useful for studying quantum effects on non-integrable Hamiltonian systems.

In plasma physics one often uses ray equations (which are Hamiltonian) to approximate a wave equation. In complex geometry the ray equations are non-integrable, and the question arises as to how this non-integrability is reflected in the underlying wave equation. This is our motivation for studying the Schrödinger equation corresponding to the standard map.

An important observation about the quantum standard map is that the quasi-energy spectrum is (in general) discrete:

$$\psi(x,t) = \sum_i a_i \, e^{-i\omega_i t} \, \psi_i(x)$$

where ω_i is a quasi-energy level and $\psi_i(x)$ an Anderson localized state.[1] The time evolution is then almost-periodic and diffusion cannot occur.

We add noise to the quantum standard map, [$\varepsilon \sin x_n \rightarrow \varepsilon \sin x_n + \nu \sqrt{2}\Delta_n \cos(x_n + \delta_n)$; Δ_n gaussian, δ_n uniform]. We find:

1)Diffusion is restored, and $D \propto \nu^2$ for ν small, $(D \equiv (\langle p^2\rangle - \langle p_o^2\rangle)/2(t-t_o))$

2)When $\nu > h$, $D = D_{cl}$, where D_{cl} is the classical value of the diffusion coefficient.

3)For $h > \varepsilon$ and small noise level ν, $D = \nu^2/2$.

We will also discuss the scaling behavior of D/D_{cl} and numerical results.

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*Work supported by USDOE.

Magnetic Field Effects On Pellet Ablation in High Temperature Plasmas

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One of the most promising methods of fueling a Tokamak fusion device is the injection of pellets of frozen hydrogen isotopes into the hot plasma. Fueling parameters such as injection speed, frequency, pellet size etc., depend critically on the ablation rate which in turn depends on the type of "shield" that is formed around the pellet. There are other factors which influence the ablation rate and which have not been adequately addressed in the various models, namely, the geometric effects associated with the presence of magnetic fields. We address these problems in this paper by assuming that the magnetic surfaces are also ablation surfaces. We calculate the ablation rate for such a geometry and compare it to that of purely spherical ablation. We find that the ablation rate is reduced by about 18% when a 0.3 cm pellet is injected into a plasma whose density and temperature are $2x10^{14}cm^{-3}$ and 10 keV respectively, and whose magnetic field is 30 kilogauss. When this effect is added to the flux reduction factor computed for purely spherical ablation one can readily conclude that magnetic field effects can safely be ignored in the calculation of pellet lifetime.

NONLINEAR STABILITY ANALYSIS VIA THE METHOD OF INVARIANT MANIFOLDS AND NORMAL FORMS*

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We want to demonstrate the power of the method of the title through a comparison of its qualitative and quantitative predictions with the results of accurate numerical experiments on a particular example. To this aim we review the fundamentals of the method and its connections with bifurcation theory. We then consider as our example the problem of 2-D Rayleigh-Bénard convection for which normal-form equations (NFE) have been derived and analyzed in [1]. We show that the bifurcation scenario that we have numerically determined [2] is correctly predicted by the NFE. Moreover, a refined version of the NFE yields a remarkably accurate value for the Rayleigh number at which a secondary bifurcation occurs; it also accurately predicts which of two coexisting, locally stable steady states will be approached as the time tends to infinity by growing perturbations of the purely conductive solution. The NFE also predicts the existence of damped oscillatory solutions which are recovered through numerical experiments. The analytic estimate of the period is in good agreement with its numerically computed value. It is doubtful that a blind, purely numerical search for such oscillatory solutions would have been successful. Furthermore, the amount of programming and computer time needed to determine the bifurcation scenario from the NFE is negligible as compared with the corresponding cost of the numerical experiments reported in [2]. These results suggest that new and perhaps more efficient and easier to implement nonlinearly stable fusion plasma configurations can be found at a minimal cost using the method described here. We are currently studying the possibility of applying the method to plasma and MHD instabilities.

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THE EFFECTS OF FOCUSING ON LOWER HYBRID WAVES*

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Ray tracing codes are the principal tools used to study the propagation of radiation in complicated geometries. While such codes can in principle provide detailed information about the wave amplitude as well as its trajectory in phase space, previous codes have not done so correctly because of the difficulty of computing accurate second derivatives of the dispersion relation, which are required in order to include focusing effects. This has now been done with the LHTOR lower hybrid toroidal ray tracing code.

There are several reasons motivating this effort, ranging from those internal to the theory to those relating to the real world. The theory is incomplete without focusing effects because either amplitudes are ignored or they do not conserve energy. A study of the energy equation with focusing included can provide information about the limits of validity of the eikonal approximation by revealing singularities where the underlying asymptotic series fails to converge. These singularities can be identified as caustics, focal points, and mode conversion zones, which require a local full wave boundary layer analysis. Correct evaluation of amplitudes is important for nonlinear studies. Finally, a possible explanation for the observed failure of lower hybrid ion heating may be found in reflection from mode conversion layers in the vicinity of high ion cyclotron harmonics. A ray tracing code incorporating the effects of ion magnetization and focusing can be used to locate and characterize singularities near the harmonics and can then be interfaced with a mode conversion code which properly treats these effects.

Two principal efforts will be described. First, focusing has been incorporated into the ray tracing code, and strong evidence for the correctness of the results has been obtained from agreement between the position of the focal point of a bundle of rays and the position of the singular point of the focusing terms. Second, a new analytical treatment of the behavior of the solution in the vicinity of such a singularity has been carried out, which considerably enhances the comprehensibility of the numerical results. A variety of examples will be presented for lower hybrid rays propagating in a tokamak.

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Saturation and Diffusion of Drift Instabilities*

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It has been pointed out recently that the saturation of coherent collisionless drift instabilities in a shearless slab is closely related to the electron nonlinear $\underset{\sim}{E} \times \underset{\sim}{B}$ convection and that the resulting diffusion is mainly caused by the electron velocity-space nonlinearity.[1,2] In the present paper, we have investigated the relevance of these mechanisms for turbulent drift instabilities using a two-dimensional gyrokinetic particle simulation code.[3] It is found that the saturation amplitude and the diffusion coefficient remain very close to the values prescribed by the more coherent cases, despite the fact that the wavenumber and frequency spectra are considerably broadened by the inverse energy cascade due to the ion nonlinear $\underset{\sim}{E} \times \underset{\sim}{B}$ convection. In addition, we have studied the effect of the nonlinearities associated with the electrons on the collisional drift waves. The initial results have indicated that the electron nonlinear $\underset{\sim}{E} \times \underset{\sim}{B}$ convection again causes the saturation. Moreover, the saturation amplitude appears to be weakly dependent on the collision frequency. Details will be presented.

*This work is supported by U.S. DoE Contract No. DE-ACO2-76-CHO-3073.

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Ballooning Instabilities Due to Energetic Trapped Particles*

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The influence of hot trapped beam ions on high-n MHD ballooning modes is studied in the frequency range of the hot particle precession frequency. An instability is found with a threshold of the same type as found earlier for the internal kink mode.[1] For a small shear, a two space scale averaging procedure is carried out and a dispersion relation of the same form as in Ref. 1 is obtained near marginal MHD stability. The threshold may be written

$$\langle \beta_h I \rangle \geq \frac{2\sqrt{2}}{\pi} \frac{\bar{\omega}_{dm}}{\omega_A} \frac{\varepsilon}{q^2} s$$

where β_h is the hot particle β, $I \sim 1$ is a geometrical factor due to bounce average, $\bar{\omega}_{dm}$ is a typical precession frequency and the remaining notations are standard.

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†On leave of absence from Institute for Electromagnetic Field Theory Chalmers University of Technology, Göteborg, Sweden

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Non-Local Transport in Tokamaks*

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Monte Carlo codes can be used to account for the effects of large orbits and loss-regions if their results are interpreted in a non-local manner.

In a tokamak, because of axisymmetry, the orbits equations can be integrated by using three constants-of-motion (COM), the energy ϵ, the magnetic moment μ, and the toroidal canonical angular momentum P_ϕ. Even a large collisionless orbit is just a point in COM space. When collisions are introduced, the motion of an individual particle in COM space resembles a random walk process and the collisionless motion of the particle can be separated from its collisional motion.

The variables used for the calculation are ψ, ϵ, μ, and P_ϕ. In this space, the Jacobian is $(v_d \cdot \nabla\psi)^{-1}$, which is just the fraction of time spent at any point along the orbit. The topology of this space is examined to determine the locus of allowed particle orbits and the loss region boundary.

To calculate the density and flux, Monte Carlo particles are followed in real space by integrating the equation for $dv_{\parallel}/dt$. After each integration step, pitch angle and energy scattering occur and the new COM are calculated. The new values of ψ_{max} and ψ_{min} are calculated numerically to determine whether the orbit crossed the surface ψ for the first time. If it did so, the change in flux is given by the mapping of $(\Delta\psi)/(\Delta t)$ onto $(\Delta\psi_{max,min})/(\Delta t)$. The density can be obtained by integrating $f(\epsilon,\mu,P_\phi)$ over the portion of COM space containing those orbits which pass through the flux surface.

The principal advantage of this method is that it separates the motion of the particles along their collisionless orbits from their collisional motion between orbits.

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+Computer Sciences Division.

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QUASI-LINEAR DYNAMO FROM RESISTIVE PRESSURE-DRIVEN INSTABILITIES*

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The Hewett/Freidberg linear resitive MHD stability code was used to calculate the radial eigenfunctions of resistive interchange instabilities in the Reversed-Field Pinch (RFP). These data were used to calculate the quasi-linear dynamo emf, $\langle \underset{\sim}{b} \times \underset{\sim}{v} \rangle_{\vartheta,z}$ (here $\underset{\sim}{b}$ and $\underset{\sim}{v}$ are the magnetic and fluid velocity field fluctuations, and $\langle\ \rangle_{\vartheta,z}$ indicates an average over the poloidal and axial directions).

The resultant poloidal dynamo emf is found to be negative inside of reversal, zero at reversal and positive between reversal and the wall. This emf will oppose the resistive decay of toroidal magnetic flux inside of reversal. However, the lack of a dynamo emf at reversal prohibits the quasi-linear evolution of resistive pressure-driven modes from causing the increase in positive toroidal magnetic flux (i.e., the flux inside of reversal) that occurs on the ZT-40 device at Los Alamos.

*Work performed under the auspices of the US Department of Energy.

ELECTRON-CYCLOTRON MASER INSTABILITY IN MAGNETIC MIRROR MACHINES*

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The electron-cyclotron maser instability for energetic electrons with a loss-cone distribution function is studied for magnetic mirror machines. The instability can occur at all angles of propagation for a wide range of parameters. The growth rate is significantly reduced by the presence of a population of cold electrons, and the instability can be suppressed if the density of the cold electrons is sufficiently large and the temperature of the energetic electrons is not too high.

*Research supported by ONR and NASA

**NAS/NRC Resident Research Associate

Analytic Stellarator Equilibria with Ellipticity

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The stellarator expansion* is known to be a good approximation for the calculation of the three dimensional stellarator equilibria. A two dimensional partial differential equation* for the leading order flux function ψ_0 is obtained using the expansion. Since the function ψ_0 is associated with all other physical quantities, we need to solve the nonlinear partial differential equation for ψ_0. As an effective way of solving this equation a variational method is used to reduce the partial differential equation to a set of ordinary differential equations. In this study the leading order flux function is approximated by shifted, elliptical surfaces. Similar work was done for shifted circular flux surfaces.** Application of the results to ATF-like plasmas will be presented.

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*J.M. Greene and J.L. Johnson, Phys. Fluids 4, 875 (1961).

**The result was presented at the APS conference 1983.

Nonlinear Depletion of Lower-Hybrid Waves.

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The numerical code LHQM is a lower-hybrid ray tracing code which includes nonlinear effects. It computes, in particular, the growth rates for the quasi-mode decay instability either along the pump rays, or along lower-hybrid daughter wave rays. When the growth rate is integrated along the daughter wave rays the energy amplification of these waves is obtained. The problem of nonlinear pump absorption in lower-hybrid wave launching is examined for PLT parameters. Preliminary results indicate that large daughter wave energy amplification is obtained at the plasma periphery in the high density regime ($n = 5.0 \times 10^{13}$ cm^{-3}). Little amplification is obtained at low density ($n < 1.0 \times 10^{13}$ cm^{-3}). The large amplification is limited to the edge region of PLT. The mechanism responsible for the localization of the amplification is presented. The pump depletion associated with large amplification is estimated. Implications for the density limit for current drive are discussed. The effect of increasing the pump frequency is also investigated.

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AN ANALYSIS OF SINGLE-WAVE PARTICLE ORBITS BASED ON CONSTANTS OF MOTION WITH APPLICATION TO SIMULATIONS OF THE ALFVEN ION-CYCLOTRON INSTABILITY

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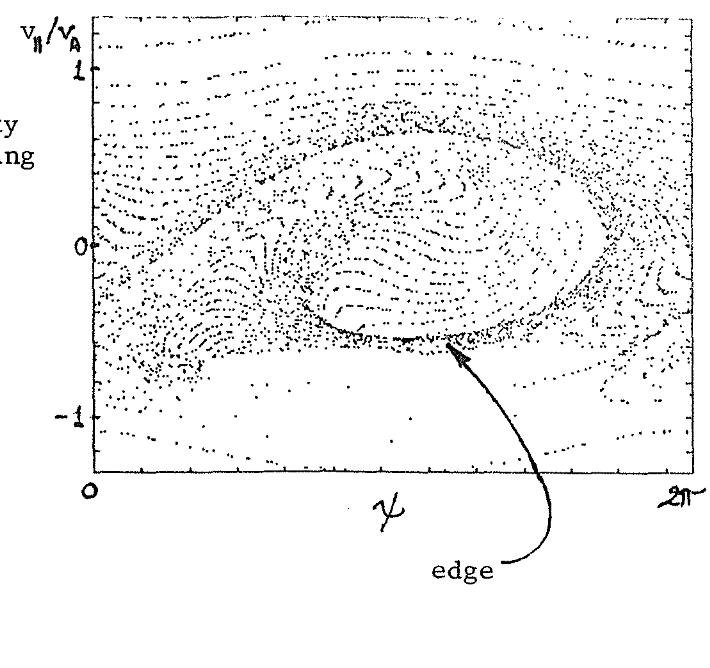
Three exact constants of the motion have been found for particles moving in a single, circularly-polarized wave propagating along a uniform background magnetic field. The constant corresponding to the helical symmetry of the system fields, C, is of particular interest because it permanently restricts each particle to a relatively small region of $v_\perp$-v_z space which generally moves to higher v_z with increasing wave amplitude. Confinement of particles to one of these regions was verified in single-wave computer simulations of the Alfvén-ion-cyclotron instability. Existence of the three constants of motion reduces the problem to motion of the particle on a two-dimensional surface in $v_\perp$-v_z-ψ space. When the wave amplitude is slowly varying, the motion on this surface is characterized by the existence and slow time-scale motion of fixed points. At least one stable fixed point always exists and its deeply trapped particles exhibit an adiabatic invariant, namely, the action J. It is hypothesized that particle trapping, fixed point motion, and the existence of J may be responsible for the appearence of an edge in the v_z-distribution function shortly after wave saturation. The edge in the distribution function is also observed in some multiwave simulations, suggesting that some of the single-wave features of the particle motion may still be present even though the principal basis for the analysis, the conservation of C, is no longer valid.

Snapshot from a single-wave simulation of the Alfven ion-cyclotron instability showing the edge in the parallel velocity distribution and particle trapping in ψ, the gyrophase relative to the wave magnetic field.



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Computations facilities provided by NMFECC.

THE EFFECT OF TENSOR VISCOSITY ON MAGNETOSONIC WAVES*

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The effect of the full tensor viscosity operator[1] on the spectrum of magnetosonic waves will be presented in slab and cylindrical geometries.

In particular, it will be shown that the effect of the large parallel viscosity on compressional waves propagating nearly perpendicular to the field is to reduce their frequency to approximately $2k_{\parallel}V_A$, twice the frequency of the shear wave.

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RF INDUCED TRANSPORT IN ICRF MINORITY HEATING*

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Recent ICRF experiments on tokamaks have reported enhanced levels of impurity radiation which in some cases could account for a significant fraction of the rf power. This increase in radiation is often accompanied by a decrease in heating efficiency. The large impurity enhancement may be due to (1) induced transport of bulk ions, (2) creation of unconfined energetic ions near the plasma periphery, or (3) other mechanisms affecting the edge. We present here a quantitative estimate of the effect due to (1) for minority heating at relatively high concentration. The induced fluxes are calculated most conveniently using a formalism by Antonsen[1] in which the fluxes are expressed in terms of solutions of adjoint equations developed in neoclassical transport theory. These equations are solved by expanding in appropriate basis functions valid for general mass ratio of the two ion species. Conditions under which radial flux enhancement occurs will be elucidated.

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*Work supported by U.S. DOE Contract DE-AT03-84ER53158.

Density Limit for Lower Hybrid Current Drive*

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Previously, we presented [1] a simple current drive model which showed that absorption by the hydrogen minority, in a deuterium plasma, could explain the current drive density limit observed on PLT. Experimental verification of this idea has been obtained by the FT group.[2] They observed the onset of hydrogen tail formation at a density equal to their current drive density limit. We have included quasilinear ion absorption in our lower hybrid modeling code to further investigate the effect of the hydrogen minority on lower hybrid current drive. We also present some results for current ramp up on PLT.

The density limit on PLT and FT occurs at densities well below mode conversion density where heating of the majority ion is expected. The onset of hydrogen absorption (via unmagnetized Landau damping) depends on a number of parameters but can occur at a density significately below the density for mode conversion. We solve for the ion distribution function as a function of radius and perpendicular velocity. The effect of rf quasilinear diffusion, coulomb collisions, and radial losses are included. Ions with large perpendicular velocities can be lost due to extended banana orbits and also to magnetic ripple trapping. Ripple trapping has previously been demonstrated to be important for majority absorption.[3]

The lower hybrid modelling code calculates the electron and ion distribution self-consistently with the quasilinear damping of the lower hybrid waves by the electrons and ions. The evolving current profile is used to compute ray trajectories. The effect of the self-consistently computed induction electric field on the rf driven current in included. Model density limits will be compared with the experimental density limits. We will also present low density ramp up results for PLT.

*This work is supported by U.S. DoE Contract No. DE-AC02-76-CHO-3073.

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SINGLE-CELL MIRROR WITH PUMPED THERMAL BARRIERS

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Recently, Catto and Taylor[1] examined the concept of a single magnetic mirror cell utilizing both sloshing ions and sloshing electrons to create ion end plugging potentials and thermal barriers. This paper generalizes the Catto and Taylor formulation to include pumping of the thermal barriers and finite sloshing population density at the midplane. Rough estimates of the performance of a reactor based on the concept will be presented.

Without barrier pumping, extremely high energy electrons are required along with large sloshing density ratios to achieve Q (≡ fusion power/input power) = 1.

With barrier pumping, sloshing density ratios ~ 10 lead to hot electron energies ~ 2 MeV for Q = 1. Since these initial estimates are very rough, the fact that they (arguably) approach a credible regime for a reactor is encouraging. Also, refinement and better guesses may allow a significantly improved design.

Because Q is not an inherent constraint for an experiment, a small-scale device based on the scheme may be of sufficient interest to warrant serious consideration.

Details of the formulation and calculations, along with results and some general considerations will be exhibited.

SHERWOOD THEORY MEETING 1984

April 11 to 13

EXPLOSIVE COALESCENCE*

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Nonlinear developments of magnetic field-line tearing, reconnection, and magnetic islands are crucial in the study of MHD activities of tokamak, RFP, and spheromak plasmas. We have been investigating[1,2] the basic mechanism of nonlinear reconnection processes, in particular, that of island coalescence. In Ref. 2 we found a fast coalescence process that obeys the Brunel-Tajima law of an algebraic increase of reconnected magnetic flux. In the present study we have identified another process of fast coalescence that exhibits an explosive increase of reconnected flux.

Analysis of particle simulation of the coalescence process shows that the magnetic energy diverges approximately as $(t_0-t)^{-2}$, the electrostatic energy as $(t_0-t)^{-4}$, the toroidal voltage as $(t_0-t)^{-2}$, the toroidal current as $(t_0-t)^{-1}$, the ion temperature in the direction of coalescence as $(t_0-t)^{-2}$, and the ion temperatures in two other directions as $(t_0-t)^{-4}$, where t_0 is the effective explosion time. Since near the explosion spatial variations are dominated by the direction of coalescence, we are able to construct a quasi-one dimensional theoretical model. We obtain analytical solutions which explain the above mentioned explosive behavior. The degree of nonlinearity of explosive MHD activities can be classified by the degree of the singularity of the temporal divergence. The explosive coalescence belongs to a pole, while the tokamak disruption to an essential singularity of $t = t_0$.

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MHD Studies of TFTR Discharges*

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The nonlinear 3-D MHD code HIB has been used to study aspects of TFTR discharges.

A. The toroidal asymmetry of the vertical field in TFTR compression experiment was studied. We find that the vertical field asymmetry produces only small magnetic islands for stable plasmas. For unstable plasmas, the development of the instability and the final saturated steady state change slightly.

B. A doubling of the sawtooth period has been observed in some TFTR discharges. This phenomenon is simulated using a hollow current profile with double $q = 1$ surfaces. We find that the helical flux ψ at the magnetic axis must be higher than the ψ values at the $q = 1$ surfaces to produce the observed phenomenon.

C. It has been proposed to detect $q = m/n$ surfaces using oscillating external (m/n) helical coil currents. The feasibility of this scheme has been studied. The results show that the time oscillation of the soft x-ray signal is not adequate for the detection of the $q = m/n$ surface. This is caused by the high level of noise coming from the pulsation of the plasma column itself. However, the toroidal variation of the x-ray signal can be used for the above purpose, if this can be measured either using multiple detector arrays along the toroidal positions or from the toroidal plasma rotation due to NBI.

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A d-^{3}He NEUTRON-LEAN FUSION REACTOR AND A ^{3}He-BREEDER SYSTEM*

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This study describes and assesses a system of several nearly neutron-free fusion reactors and their fuel breeding source. This assessment consists of the development of a conceptual nuclear polarized d-^{3}He neutron-lean reactor and a conceptual ^{3}He-breeder reactor based on the tandem mirror reactor (TMR) concept. This breeder is a d-d fusion reactor that produces ^{3}He for the neutron-lean "satellite" reactors. The assessment is made with respect to physics, engineering, cost, and safety.

The conceptual neutron-lean TMR is fueled by approximately equal amounts of deuterium and ^{3}He whose nuclei have been spin polarized +1 and +1/2, respectively. For such a fuel cycle the d-d reactions tend to be suppressed; there is experimental evidence that the d(d,n)^{3}He and the d(d,p)t reaction rates may be reduced by more than a factor of 20 (95% suppression) [1]. There is also evidence to suggest that the d(^{3}He,p)^{4}He reaction rate is enhanced by a factor of 1.5 [2]. The significance of the d-d reaction suppression is that there would be no neutrons and no tritium produced in a d-^{3}He fusion reactor if the suppression were perfect. The fusion reactor would represent no occupational hazard, could have "hands-on" maintenance, and be located within cities.

The required quantities of ^{3}He burned in the neutron-lean satellite reactors are to be generated by a TMR ^{3}He breeder. The ^{3}He breeder utilizes the standard d-d fuel cycle to produce ^{3}He in the plasma. Then ^{3}He is pumped from the plasma along with the alpha particle "ash" and separated isotopically. Another important ^{3}He source comes from Li(n,t) reactions in a lithium blanket. The tritium produced is removed from the blanket and reduced to ^{3}He by beta decay. Using the d-d fuel cycle to breed ^{3}He produces tritium and neutrons, and leads to the activations of the reactor structure and components. The safety issues for a "standard" d-t fusion reactor are comparable to this ^{3}He breeder. Precautions must be taken with respect to activations, tritium handling, and accident consequences. Accordingly, this breeder is suggested to be remotely located. This conceptually designed 3000 MW fusion power ^{3}He breeder can supply ^{3}He fuel for up to 19 neutron-lean satellite reactors; each producing ~600 MW net electric power.

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Stabilizing Influence of Hot Beam Ions on Ballooning Modes in Tokamaks*

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It has recently been proposed that the presence of both untrapped[1] and trapped[2] high energy ions from neutral beam injection can have a strong stabilizing effect on MHD ballooning modes in tokamaks. In order to realistically assess the importance of such effects, a comprehensive kinetic stability analysis[3], which takes into account the integral equation nature of the basic problem, has been applied to this investigation. For the same parameters and the same model equilibrium used in Ref. 1, the stabilizing trend reported when the fraction of hot ions and/or the hot ion temperature is increased[1], is reproduced. However, if collisions are takes into account, this favorable trend is found to persist but tends to be considerably weaker. Results of calculations using realistic beam distribution functions[4] (instead of idealized Maxwellian distributions[1]) are also presented and discussed.

*This work is supported by the U.S. DoE Contract No. DE-AC02-76-CHO-3073 .

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THERMAL CONDUCTIVITY OF ELECTRONS THROUGH A POTENTIAL BARRIER*

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The presence of a potential barrier is consistent with the observation of a high edge temperature region in the H-mode of diverted tokamak discharges.[1] At intermediate collisionalities, the heat flux carried through a potential barrier by electrons is inhibited to be below both the free streaming and the Braginskii expressions. This effect is studied numerically. The heat bath at the cold end is assumed to be totally absorbing, whereas the heat bath at the hot end is partially reflective to model a possible "mirror" confined region. The self-consistent electrostatic potential is assumed given, and a zero current condition is applied. The dependence of the thermal conduction inhibition factor on the barrier size, electron collisionality, and heat bath characteristics will be presented.

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*Work supported by U.S. DOE Contract DE-AT03-84ER53158.

PERTURBATION THEORY ANALYSIS OF ION CYCLOTRON WAVES IN EBT*

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The analysis of ion cyclotron wave propagation and related plasma heating processes in EBT is made difficult by the complex geometry of that device. In particular, the characteristic wavelengths are of the order of the device size, the approximation of geometric optics is inappropriate, and the analysis must be approached as an eigenvalue problem. Initial analytical[1] and numerical[2] studies have been undertaken but results have been complicated and difficult to understand. We present an analysis of ion cyclotron wave propagation in EBT based on the assumption that it may be approximated as a weakly bumpy cylinder. Specifically, we utilize the perturbation methodology (multiple space scales and transfer of boundary conditions) developed by Nayfeh[3] to study sound and electromagnetic wave propagation through corrugated ducts. In first order, this methodology predicts modulation of the cylindrical eigenmodes and permits study of the resonant interaction of propagating modes with the device wall. In second order, modification of the cylindrical eigenvalues are obtained. In addition, we study the effects of radial plasma inhomogeneity within the context of a cylindrical model. While these methods are unlikely to yield quantitatively accurate results for ion cyclotron wave propagation in the strongly bumpy EBT, they shed light on the basic phenomena which may occur and will serve as useful benchmarks for more comprehensive numerical studies.[2] This particular analysis evolves out of the consideration of other perturbation methodologies suggested for application to wave propagation in EBT by Cotsaftis.[4,5]

*This work was supported by the U.S. Department of Energy.

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2Q15

MATRIX ELEMENTS OF LINEARIZED FOKKER-PLANCK OPERATOR*

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Kinetic equations involving the linearized Fokker-Planck operator can often be solved by expanding the distribution function in a basis of Burnett functions, which are the products of Legendre polynomials P_ℓ and generalized Laguerre polynomials $L_n^{(\ell + 1/2)}$. While the resulting matrix elements of the Fokker-Planck operator for small values of ℓ can be obtained from generating functions existing in the literature, the generating functions for arbitrarily large ℓ do not seem to have been derived. We have decomposed the generating functions into parts, for which recursion relations in ℓ can be derived. Simple FORTRAN programs which evaluate product and quotient of polynomials of two variables have been written. In conjunction with the recursion relations, they enable the matrix elements to be generated with great computational speed. Similar techniques are applicable to other terms in a typical linearized kinetic equation such as the ballistic term and the magnetic mirror force term. The resulting matrix equation involves a band tridiagonal matrix, and can be readily inverted. Illustrations are taken from neoclassical transport theory.

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SHERWOOD THEORY MEETING 1984

April 11 to 13

NONLINEAR LANDAU DAMPING OF PURELY PERPENDICULAR BERNSTEIN MODES*

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The linear dispersion relation for Bernstein modes, obtained by the integration of Vlasov's equation along the unperturbed cyclotron orbits, predicts that the modes propagating perpendicularly to the magnetic field are undamped, i.e. $\gamma_L \to 0$ as $k_\parallel \to 0$. However, when ω is close to a resonance $\omega_n = n\Omega_c$, most of the particles become trapped for arbitrary small wave amplitude E and the unperturbed orbit approximation breaks down. The trapped particle trajectories are calculated analytically here using a resonant Hamiltonian approximation. Integration along the new orbits, consistent with the wave, yields the damping rate γ_{NL} in a similar manner as the one used by O'Neil for the damping of unmagnetized electrostatic modes. It is found that for typical fusion devices parameters γ_{NL} is quite large implying the possibility of Bernstein mode heating.

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Heat Pulse Propagation to Determine the Electron Diffusivity χ_e*.

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During recent years, the question of radial electron heat conduction as the dominant transport loss in the tokamak, has been addressed in many ways. However, few methods have been available to directly measure the electron heat diffusivity coefficient. The sawtooth oscillation as a heat pulse mechanism to measure χ_e has been discussed in detail [1]. This method of estimating χ_e appears attractive, when studying sawteeth on a large tokamak like TFTR where the heat pulse propagation time can be as long as 30ms.

Numerical work confirms a simplification to the classical heat pulse problem which allows not only the peak of the heat pulse, but fractional values of the peak perturbation, to give information directly on χ_e (assuming χ_e and n_e are constant with radius). Comparison of measured χ_e values for different plasma current, minor radius and line averaged density on TFTR have been made. The results are then used to compare with the confinement scaling laws obtained from power balance calculations.

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SHERWOOD THEORY MEETING 1984

April 11 to 13

ACTION JUMPS AND THEIR RELATION TO STRONG TURBULENCE THEORY*

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When a weak explicit time dependence is added to the Hamiltonian of an integrable system, the first integrals of the motion become "adiabatic invariants" which are approximately conserved except where phase space orbits cross separatrices of the instantaneous phase flow. The jump in action and its probability distribution for a very general type of slow separatrix crossing are derived. Both are compared to computer simulation.

Knowledge of this action jump allows one to calculate the diffusion coefficient for particles moving in a turbulent electrostatic field with a narrow frequency spectrum. While a "strong turbulence" theory for this regime has been developed;[1] recent numerical experiments[2-4] tend not to support it. To develop an understanding of the narrow spectrum case, a model with a single wavevector and a narrow frequency spread $\Delta\omega$ is considered. This is equivalent to an electric field of the form $E(x,t) = E(t)\cos[kx - \phi(t)]$. In the strong turbulence limit ($\Delta\omega^3 \ll k^2 D_{QL}$, where D_{QL} is the quasilinear diffusion coefficient) the amplitude and phase vary slowly on the bounce-time scale, $\partial\, \ell nE/\partial t,\ \partial\phi/\partial t \ll \omega_b \equiv |ekE/m|^{1/2}$. Thus, the action of a particle is well conserved except when it is near the separatrix, where the previously mentioned jumps in the particle action occur. When summed, these jumps lead to a diffusion of the action which scales as $D \sim \Delta\omega^3$ in contrast to the scaling of $D_{QL} \sim \omega_b^4/\Delta\omega$. This scaling and other aspects of the present theory differ substantially from the previous strong turbulence theory. Comparisons of these results with numerical experiments are presented.

*This work is supported by the U.S. Department of Energy and the Center for Studies in Statistical Mechanics, University of Texas, Austin, TX 78712.

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MODELING AMBIPOLAR POTENTIAL FORMATION DUE TO ICRF HEATING EFFECTS ON ELECTRONS*

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A proposed mechanism for the potential bump observed near the region of ICRF heating in the end plugs of the Phaedrus tandem mirror experiment is investigated by numerical simulation of electron particle orbits in a simple mirror geometry. Given initial magnetic and ambipolar potential wells that trap the electrons, the "near field" parallel electric field $\tilde{E}_z e^{-i\omega t}$, which is localized near and due to the ICRF heating, tends to eject electrons from the region where $\tilde{E}_z$ is nonzero. This depletion of the local electron population can cause a local increase in the ambipolar potential. The numerical simulation of electron particle orbits in the presence of the $\tilde{E}_z$ field is being utilized to develop a quantitative model for this proposed mechanism of potential formation.

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THE BIG DEE UPGRADE OF DOUBLET III*

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Initial operation of the Big Dee[1] tokamak (an upgrade of the Doublet III device into a device with major radius $R = 1.67$ m, minor radius $a = 0.67$ m, and half height $b = 1.4$ m) is anticipated in early 1986. The low aspect ratio ε and high elongation κ enable the device to attain high plasma current within conventional limits on the safety factor. Big Dee shaping and control systems which are a simple extension of those already in use on Doublet III will allow uniquely precise control of elongation and triangularity. Comparisons[2] of model calculations with the results obtained on other existing devices have shown good agreement between experimental results and the values of limiting β, β_c, obtained from equilibria stable to ballooning modes with limiter safety factor $q_\ell \geq 2$. Theoretical predictions indicate that the Big Dee should be able to attain reactor relevant values of the plasma pressure $<p>$ in a modest sized device. A β limit for the Big Dee can vary from 11.0% (assuming no wall stabilization of the kink mode) to over 21.0% (assuming a cold plasma mantle or limiter stabilization of the kink mode). We have obtained dee-shaped equilibria which are stable to ballooning modes with $\beta_c = 17.2\%$ and $q_\ell \geq 2$ ($\kappa = 2.15$, $\delta = 0.45$, $I_p = 5$ MA, $B_T = 1.49$ T, $\beta_p = 0.46$). Optimization for maximal pressure results in $<p> = 2.43$ atmospheres at $I_p = 5$ MA and $B_T = 2.2$ T ($\kappa = 1.8$, $\delta = 0.40$, $q_\ell = 2.84$, $\beta_p = 0.66$). Optimization of divertor plasmas is limited by additional restrictions on plasma shaping but critical betas of 8.0% and $<p>= 1.6$ atmospheres with $I_p = 2.8$ MA and $B_T = 2.2$ T have been obtained.

Thus it is clear that there exist high β Big Dee equilibria in desirable operating regions. We show that the β limits for the Big Dee are consistent with established theory as summarized in recent scaling laws, and we demonstrate that the attractive high β Big Dee equilibria are continuously accessible when approached through changes in all relevant input plasma parameters. We show that the equilibria are structurally stable with respect to variations of the input plasma parameters. We demonstrate the smooth dependence of Big Dee β limits on plasma parameters such as β_p and elongation. Theory predicts that the limiting plasma parameters (such as β_p, I_p and $<p>$) which can be attained within the operating limits of the Big Dee are reactor relevant. Thus the Big Dee should be able to use its favourable ideal MHD scaling and controlled plasma shaping to attain reactor relevant parameters in a moderate size device.

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Propagation and Absorption of Electromagnetic Waves In Fully Relativistic Plasmas*

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Propagation and absorption of electromagnetic waves in a relativistic Maxwellian plasma are investigated by solving the uniform plasma dispersion relation. Both the Hermitian and the anti-Hermitian parts of the plasma conductivity tensor $\underset{\approx}{\sigma}$ are calculated relativistically. The Bessel functions occurring in $\underset{\approx}{\sigma}$ are not expanded, and many cyclotron harmonic terms are included at high temperatures. The dispersion relation is solved numerically for perpendicular propagation, $k_{\parallel} = 0$, where the relativistic effects are maximum and are not marked by Doppler broadening, which has been more thoroughly investigated. It is found that relativistic broadening has a substantial effect on wave dispersion, shifting the extraordinary mode right-hand cutoff and upper hybrid resonance to higher magnetic field with increasing temperature. Above a critical temperature the cutoff disappears entirely. There is a broad range of temperatures, 20 keV $\lesssim T_e \lesssim$ 500 keV, for which the wave number $k_{\perp}$ differs significantly from both the cold plasma value and the vacuum value. This has important implications for ray tracing in relativistic plasmas. Wave damping rates are calculated and compared to results from a previous formulation using Poynting's theorem, in which only the Hermitian part of $\underset{\approx}{\sigma}$ is calculated relativistically.

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Particle Loss Rates from Electrostatic Wells of Arbitrary Mirror Ratios*

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Prior to the introduction of thermal barriers to the tandem mirror concept the mirror program expended a considerable effort to evaluate loss rates from magnetic traps in the absence of a significant electrostatic field and, more recently, in the presence of a strong confining electrostatic potential. In order to implement thermal barriers in current tandem mirror designs, however, it has been found necessary to create the electrostatic well for the plug electrons in a region of increasing magnetic field. In the Upgrade Tandem Mirror Experiment (TMX-U), for example, the ratio of the magnetic field at the plug potential to that at the minimum of the plug magnetic field (where the thermal barrier is located) is between one half and three quarters. Therefore, in order to evaluate the loss rate of the electrons from the plug, an expression for the loss rate from an electrostatic trap is required which is valid for mirror ratios less than or on the order unity.

Single integral expressions for the particle loss rate from an electrostatic trap with $Ze\Phi_o/T \gg 1$ are derived which span all possible mirror ratios R, where Φ_o, Z, and T are the potential well depth, charge number, and species temperature. The two expressions are shown to be identical for a range of intermediate R so that one expression is valid for small to intermediate R ($R \lesssim 1$), while the other is appropriate from intermediate to large R ($R \gg T/Ze\Phi_o$). Three particularly simple analytic limits are found to exist: (i) $R \ll T/Ze\Phi_o$, (ii) $T/Ze\Phi_o \ll R \lesssim 1$, and (iii) $R \gg 1$.

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The Spectrum of the MHD and Kinetic Alfvén Waves in a Cylindrical Tokamak*

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The ideal MHD Hain-Lüst[1] equation yields the well-known continuum of shear Alfvén waves defined by $\omega_A^2|_{min} \leq \omega^2 \leq \omega_A^2|_{max}$, $\omega_A^2 = k_{||}^2 v_A^2$, $(k_{||} \neq 0)$. This second-order differential equation also possesses discrete spectra for $\omega^2 < \omega_A^2|_{min}$, recently investigated by Appert, et al.[2] We find for a cylindrical Tokamak that the discrete modes vanish if $\frac{\partial}{\partial r}(k_{||}^2)$ is positive, or in the presence of a flat density profile. As the toroidal mode number ℓ decreases, the accumulation point moves down from $\omega_A^2|_{min}$. Transformation to a Schrödinger-like equation makes the existence and disappearance of these states particularly transparent. In the region above the continuum $\omega^2 > \omega_A^2|_{max}$, the normal (negative-gradient) density profile forbids the existence of a discrete spectrum from the second-order MHD equation.

The lowest order finite gyroradius correction to the ideal MHD equation yields a fourth-order radial differential equation which removes the Alfvén continuum and a discrete spectrum appears.[3] Where second-order equation discrete states do exist, the fourth-order equation perturbs them, raising the eigenvalues and removing the accumulation point.

In the frequency regime $\omega^2 > \omega_A^2|_{max}$ we find that when the second-order equation has no discrete states the fourth-order equation permits them, with the eigenvalues ω_n^2 increasing with the radial quantum number n. WKB predictions of high eigenvalues $(\omega_n^2 > \omega_A^2|_{max})$ agree with the numerical calculations.

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A STUDY OF MODE COUPLING AT $\omega = 2\omega_{ci}$

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We study the mode coupling at the ion cyclotron harmonic $\omega = 2\,\omega_{ci}$ in a non-local, i.e. eikonal plus B-field gradient, approximation [1]. The dispersion relation is derived directly from the Vlasov-Maxwell equation, assuming a uniform plasma and a linear spatial variation in the static magnetic field in the direction which is normal to the magnetic field direction, i.e. $\bar{B}_o(x) = B_o(1 + x/L)\bar{e}_z$ (terms of order higher than the Larmor radius square ρ_L^2 and the scale length $L^{-1} = (1/\omega_c)(d\omega_c/dx)$ are neglected). This results in the appearance of first and third derivative terms in the differential equation for the electric field, terms which do not appear in the so-called local approximation. The odd power terms substantially modify the local dispersion relation, the principal effect being the breaking of symmetry of the complex roots around the line $k_\perp = 0$. Results obtained for the Alcator C parameters (T_i = 800 ev, B = 6.55 T, $N_o = 6 \times 10^{14}$ cm^{-3}) show that this modification of the dispersion relation is important in the range of projected k_z values (0.05 cm^{-1} to 0.16 cm^{-1}). We investigate the asymmetry, with respect to the direction of incidence, of the transmission and damping properties for this mode coupling problem.

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USE OF LOCAL DISPERSION RELATION AROUND THE MODE CONVERSION LAYER AND CONNECTION WITH WKB THEORY*

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It is generally known that WKB theory breaks down near the mode conversion layer and hence it was generally assumed that one cannot obtain physical information from the local dispersion relation. In a set of wave equations describing mode conversion near the ion cyclotron range of frequencies, we decompose the solution into four components, each corresponding to a branch in the local dispersion relation over the entire region. This is done by explicit construction. While each component is not a solution by itself, the decomposition is unique and can always be done numerically. From this decomposition, one can study the detailed physics of mode conversion process, and in particular, we find it is still possible to obtain useful information from studying the local dispersion.

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STUDIES OF ACCELERATION OF COMPACT TOROIDS*

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Studies of acceleration of compact toroids reported earlier[1] have been extended by: (1) analytic treatment of long thin CT equilibria between cylindrical or conical coaxial electrodes including uniform acceleration, (2) numerical computation of 2-D equilibria and 3-D, ideal MHD stability, (3) numerical simulation using a 2-D MHD code and (4) 0-D calculations of CT acceleration including radiation and resistive drag. Axially bounded analytic equilibria between coaxial electrodes are found only if small departures from the Taylor state ($rB_\phi \propto \psi$) are allowed as, for example, $rB_\phi \propto \psi + \delta\psi^2$, or if acceleration or conical electrodes are introduced. Persistent tilt instability is found except for some accelerated states. 2-D numerical simulation of adiabatic ring compression, acceleration, and focusing agree with, and extend, 0-D calculations reported earlier.[1] The effects of wall ablation have been studied and selected applications have been simulated including a fast-opening switch, and a CT-driven, stabilized, linear pinch. 0-D calculations include non-equilibrium impurity line radiation to follow the plasma temperature and pressure evolution, and magnetic field decay during acceleration.

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** Consultant to LLNL from S. Levy Inc., Campbell, California.

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COLLISIONLESS NEOCLASSICAL NONRESONANT TRANSPORT IN BUMPY TORI*

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ABSTRACT

Neoclassical diffusion coefficients for a bumpy torus were first computed by Kovrizhnykh. He showed that for low collisionalities the transport rates scaled with collisionality. However, he ignored many important effects and recent theoretical work in the collisionless limit indicates that substantial modifications need to be made to his diffusion coefficients. First, in a closed field line device the pressure surfaces can deviate substantially from the |B| surfaces and, in addition, can have some ellipticity. It is found that the effect of ellipticity enters in the same way as a tokamak while the shift of the pressure surfaces modifies the radial drift and, hence, the diffusion coefficients. Second, in a bumpy torus there can be a significant poloidal electric field which enhances the radial the radial drift and therefore the transport rates. This can be calculated self-consistently from the requirement of first order quasineutrality. Third, when a realistic magnetic geometry is used in bounce averaging the differential collision operator it is found that particles near the trapped/passing boundary make a larger contribution to the transport than indicated in Kovrizhnyh's work. In particular, it is found that for collisionalities close to one, a collisional boundary layer forms across the trapped/passing boundary and this leads to diffusion coefficients scaling with the square root of collisionality. For lower collisionalities, the effect of collisionless detrapping is important and this leads to transport rates scaling with collisionality, but with the inverse aspect ratio rather than its square. When these results are generalized to multiple-ion species plasma, it is found that energy coupling between the different ion species can produce significant modifications of the diffusion coefficients. The new diffusion coefficients with all these effects included have been confirmed with the use of a Monte Carlo code developed for bumpy tori. Finally, the use of these transport rates in 1-1/2D radial transport codes indicates much lower lifetimes than obtained with the Kovrizhnykh coefficients. The lifetimes now obtained are within a factor of 2 of the experimentally observed numbers.

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BALLOONING MODES IN THE ELMO BUMPY SQUARE CONFIGURATION USING THE GENERALIZED KINETIC ENERGY PRINCIPLE*

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ABSTRACT

In the bumpy square configuration, toroidal curvature is localized in the corner sections rather than uniformly distributed as is the case in the existing circular EBT configuration. This feature, coupled with the fact that the magnetic field is higher in the corner sections, results in a number of distinct advantages with respect to particle confinement, heating and transport. It might be expected, however, that ballooning modes should have some tendency to concentrate in the corner sections - especially along the outer field lines where the curvature and pressure gradients are unfavorable. Here we examine the stability of such a configuration using a ballooning mode equation[1] derived from the generalized kinetic energy principle.[2,3] The side and corner sections of the square are treated with a piecewise constant approximation and matched at a transition boundary to obtain the stability condition. This retains the ring-core coupling and yields both the low β_c diamagnetic well stabilization condition and a high β_c stability limit analagous to the Van Dam-Lee-Nelson β_c limit. Due to the high magnetic field in the corners and the relatively weak curvature there ($\simeq \frac{1}{2}$ of the curvature in the bumpy sections), this upper β_c limit is not significantly changed from that which would be present in the conventional circular bumpy torus configuration.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

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COLLECTIVE MODES IN SPIN POLARIZED PLASMAS.

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Electromagnetic modes with frequencies in the ion cyclotron range of two-ion species plasmas with polarized spins [1] can be driven unstable by the anisotropy in the velocity distribution of the fusion reaction products and can cause a relatively high rate of depolarization of the fusing nuclei. This has been shown for a homogeneous plasma model in Ref. [2].

We have derived a dispersion equation for a D,T plasma in a toroidal configuration that incorporates the inhomogeneities of the plasma density and of the magnetic field. For frequencies around the sixth-harmonic of the α-particle cyclotron frequency Ω_α that are appropriate to resonate with the triton spin precession frequency $\Omega_T^{(P)} \simeq 5.96\Omega_\alpha$ it is possible to construct normal mode solutions with sufficiently small effective parallel wave numbers to avoid a significant electron transit time damping for a reasonable range of values of $\beta_e = 8\pi n T_e / B^2$

The relevant modes are radially localized on a scale distance $\sim (a d_i)^{1/2}$ that is long compared to the mode poloidal wavelength and short compared to a (a is the plasma minor radius and d_i is the inertial ion skin depth). These modes resonate with the α-particles via their magnetic curvature drifts and are likely to reach amplitudes sufficient to depolarize the triton spins.

Instead, when considering frequencies near the deuteron precession frequency, $\Omega_D^{(P)} \simeq 0.87\,\Omega_\alpha$, the presence of an ion hybrid cutoff-resonance pair makes it difficult to reduce the effective longitudinal wave number to the low values desired. It this case it is an open question whether well defined normal modes exist with a weak damping rate. These could conceivably be driven to a sufficient amplitude to cause deuteron depolarization by some form of coupling (e.g. nonlinear) to other excited modes.

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ALPHA EFFECT AND BETA EFFECT DYNAMOS

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Analytical prediction of amplification of large-scale magnetic fields by small-scale MHD turbulence seems to have originated with Steenbeck, Krause, and Rädler's 1966 calculations of the "alpha effect" dynamo. Microfluctuation spectra with net helicity could be shown, under certain assumptions, to generate an average e.m.f. proportional to the mean magnetic field, and to lead to amplification of it. The process is related to, but not exactly the same as, an inverse cascade, in that the back-transfer is assumed to be highly non-local in wavenumber space. A related, but distinct, mechanism can be called the "beta effect," in that the amplifying terms are associated with Laplacians of the large-scale magnetic field[1] rather than with curls[2] of it, and no net helicity is required: the effect may occur when the alpha coefficients vanish identically. The beta effect is essentially a 2D MHD effect, and can be demonstrated for the Strauss equations of "reduced" MHD when their behavior is essentially indistinguishable from that of 2D MHD: what is required is an excess of microscopic magnetic turbulent energy over kinetic. Both alpha and beta coefficients are reported here for models in which the sources of microscopic magnetic and kinetic noise are independent of each other. Earlier results of Pouquet, and of Biskamp and Welter, are recovered as special cases. Either mechanism could be considered as a plausible explanation for a major disruption of a toroidal discharge (RFP _or_ tokamak), but only to the extent that appropriately confirming microscopic fluctuation spectra were measured. Also required would be the persistence of the large spectral gaps which alpha effect calculations presuppose, and which to date are not well supported by computational experience (the spectral gap often seems promptly to fill in).

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A STUDY OF THE NONLINEAR MODULATIONAL INSTABILITY*

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A simple and direct method is presented for finding exact periodic and quasiperiodic solutions of the cubic nonlinear Schrodinger equation (NLS) ($iu_t + u_{xx} + 2|u|^2 u = 0$). The NLS appears in several situations of fusion interest; for example, as the equation describing the envelopes of both Langmuir waves in strongly turbulent plasmas and cyclotron waves in magnetized plasmas.

Plane wave solutions of the NLS are well known to be unstable to long wavelength perturbations. Using a method developed by the authors exact solutions of the NLS can be constructed to study the long time behavior of a modulated plane wave.

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Calculation of HELIAC Vacuum Magnetic Field Configurations*

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The vacuum field solver described by Shestakov and Mirin[1] has been extended. Two applications of the code are presented.

The first application searches for an optimum HELIAC. An outer magnetic surface is prescribed and a Neumann problem is solved for the scalar potential. Subsequent magnetic field line integrations with the code TUBE[2] reveal the size of the magnetic well, the transform, the shear and the relative standard deviation of $\int d\ell/B$ ($\equiv \Delta Q/Q$) on the surfaces--quantities which are used to assess the worth of the configuration. Many cross sections are considered; for each, the major and helical radii, the number of helical periods and twist law are varied. The transform depends on all of these quantities. In particular, the undesirable $\iota_p = 1/3$ surface can be eliminated from the "resonant" case considered by Grossman et al.[3]. If the major and helical radii are changed to 6.85 and 1.7 respectively, then for four helical periods (case V55U), there results a well of 4.3%, internal rational ι_p of 3/8 and 5/13, and a maximum $\Delta Q/Q$ variation of $\simeq$ .11. The corresponding beta limits due to helical and toroidal shifts are respectively 0.18 and 0.28. Other results are presented.

The second application extends the code to efficiently compute the vacuum magnetic field inside a general toroidal domain[4]. Results are presented for the Princeton Reference HELIAC which consists of 24 circular TF coils interlocked with a larger, central circular coil and a uniform vertical field. Using only 6 poloidal and 4 toroidal harmonics and only 30 radial mesh points, the code agrees with the analytic field to an accuracy of better than 1%.

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ANALYTIC DYNAMO MODEL FOR THE REVERSED-FIELD PINCH

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An analytic, resistive, steady-flow MHD dynamo model is developed that is appropriate for the reversed-field pinch (RFP). The methodology used is similar to that of Lortz [1]. With this method, the associated helically symmetric equations of the model are reduced to a system of nonlinear ordinary differential equations. Although Lortz demonstrated that solutions to such a system exist, they must be found numerically.

In an RFP, a toroidal electric field generates poloidal flux that couples to toroidal flux by dynamo action. In Lortz's model, a helically symmetric, cylindrical core is surrounded by a cylindrically symmetric region. It can be shown that, for this particular model, a dynamo can exist in the neighborhood of the average toroidal field reversal only if the reversal radius is in the outer region. A generalization of the Lortz model removes this requirement and the results compare qualitatively with the numerical solutions of Aydemir and Barnes [2].

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SMALL-SCALE STRUCTURES IN CONVECTIVE TWO-DIMENSIONAL BENARD TURBULENCE

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The two-dimensional convective hydrodynamics of the Benard problem in the Boussinesq approximation is simulated with our spectral code STELLA. No chaotic thermal convection is found for parameter values such that the number of modes included satisfactorily resolves the gradients of the fully developed flow. In particular, we find coherent structures for Ra = 50 x Ra_{crit}, Pr = 10, which still fits into a 32^2 spectra grid. To further increase the Rayleigh number, we have developed the relevant statistical equations for random turbulence based on the Direct Interaction Approximation.[1-2] We discuss the resulting effective eddy damping caused by the modes beyond our spectral truncation in various approximations.

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Nonlinear Evolution of Microtearing Modes*

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It has been shown[1] that corrections of Braginskii fluid equations of order ω/ν_e introduce a new term in the Ohm's law proportional to the time derivative of the thermal force. This term can produce an instability driven by the free energy stored in the electron temperature gradient.[2] The modes are strongly localized around the singular surface and could be identified as microtearing.

We have calculated the linear stability properties of these modes in cylindrical and slab geometry and they compare favorably with the analytical dispersion relation.

We are presently investigating the nonlinear saturation in the single helicity approximation as a first step to study nonlinear interaction of modes of different helicities and breaking of magnetic surfaces. Results will be presented at the meeting.

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2R5

DRIFT TURBULENCE IN A SHEARED MAGNETIC FIELD

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The fluid equation of nonlinear drift waves in a sheared magnetic field for the electrostatic potential ϕ and the parallel ion flow V are solved numerically in slab geometry using a finite difference scheme in x and Fourier representation (m,n) in y,z. With phenomenological excitation coefficients (of not too large magnitude) a stationary turbulence level is generated. First the case of one resonant surface m/n = const is considered. Spectra are peaked at small m. The position of the maximum and the total energy depend sensitively on the small m excitation coefficients $k_y \rho_s \ll 1$, but are quite insensitive to those at high m, $k_y \rho_s \gtrsim 1$. Frequency spectra are broad at high turbulence levels. Linear mode properties are drastically changed nonlinearly. In particular is the shear damping strongly reduced. Once excited a finite turbulence level persists even if the excitation coefficients are reduced well into the linearly stable regime. An approximate analytic theory of this effect is given. The structure of the turbulence is not changed substantially if many resonant surfaces are included.

Resistive Interchange Instability in 3D Code Stellarator Equilibria

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The application of the Mercier criterion to 3D code stellarator equilibria showed that different types of stellarators exhibit different stability behavior as far as the local ideal MHD modes covered by the Mercier criterion are concerned: i) the unstable behavior of WVII-AS at $<\beta>\approx 0.01$ comes about because the destabilizing influence of the square of the PS current density grows faster than the stabilizing deepening of the magnetic well [1]; ii) the stable behavior of flux-conserving ATF-1 equilibria at $<\beta>\approx 0.03$ with a bell-shaped pressure profile does not only rely on the reversal of the above mechanism but also on the directly stabilizing interaction of the shear and the averaged parallel current density occurring in the Mercier criterion; iii) in stable nonresonant toroidal Heliac equilibria with many periods [2] the destabilizing influence of the square of the parallel current density becomes negligible. Resistive interchange modes [3] are governed by the quantity ($<\ldots>= \int \ldots \sqrt{g}\, du dv$; s, u, v flux label, poloidal and toroidal angular variables; $' = d/ds$; $X = j_{\|}/B$; $S = F_P' F_T'' - F_P'' F_T'$)

$$H = S^{-1} < B^2|\nabla s|^{-2} > \left(\frac{< XB^2 >}{< B^2 >} - \frac{< XB^2|\nabla s|^{-2} >}{< B^2|\nabla s|^{-2} >}\right)$$

Preliminary results obtained for the types of equilibria considered above are: i) $SH > 0$ in WVII-AS; the resistive criterion is so close to the ideal one that the stability limit is nearly unchanged; ii) $H < 0$ in ATF-1 ; $H \approx -3$ for $<\beta>\approx 0.03$; a drastic destabilizing influence is observed, so that even $<\beta>\approx 0.01$ is resistively unstable; iii) $0 < S < 1/2$ for a Heliac equilibrium with 10 periods and $<\beta>\approx 0.07$; the difference between the ideal and the resistive criteria is virtually vanishing.

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Determination of the Boundaries of Stochastic Regions of Phase Space for Strongly Perturbed Nonlinear Oscillators

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In recent years the criteria for the onset of global stochasticity have been studied extensively. This work has had important applications in determining the critical electric field strengths for stochastic wave heating and the critical magnetic field perturbations for stochastic field line and particle diffusion. However, a detailed description of the heating or particle loss requires the development of a statistical theory for the chaotic dynamics of these perturbed nonlinear oscillators. In many problems the stochastic motion is restricted to bounded regions of phase space. Therefore, any statistical descritpion requires the determination of the boundaries which separate the stochastic and regular regions. For small perturbations these boundaries are well approximated by the separatrices of the "overlapping", primary resonances. However, as the perturbation strength is increased, the extent of the stochastic domain is significantly enlarged by the interaction of higher order resonances. These new results are applied both to the stochastic wave heating of charged particles confined by magnetic fields and of electrons confined in atoms. These closely related problems have important applications in the respective fields of fusion physics and quantum chaos.

Long Pulse Evolution of Elongated, Rippled High-Beta Tokamaks

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ABSTRACT

We have studied the long pulse evolution of high-beta tokamaks with the New York University 3D transport-equilibrium code (3DETC)[1]. The code embodies Grad's alternating dimension algorithm for transport in nonaxisymmetric configurations[2]. The classical one-fluid, anisotropic transport model has been extended by adding models for energy sources (centrally peaked) and recycling/radiation loss (increasing toward the boundary). Ripple-plateau thermal conductivity has been added to the classical thermal loss processes to couple the 3D and 1D effects more closely.

Using parameters chosen to model the proposed DCT device[3] we have examined the existence of high-beta (5%), highly elongated (40%) and triangulated (20%) configurations which have been produced by rapid heating. We have studied ripple values typically quoted for DCT and also configurations having much higher ripple (10%). After strong and rapid heating (reaching beta=4% with $\tau_{HTG} << \tau_{SKIN}$), we find the expected FCT phase, but with accelerated flux diffusion at the edge from the ripple diffusivity. Following the FCT phase the q-profile relaxes by resistive diffusion with steadily decreasing shear. After a core skin time, only a 20-30% variation of q from the core to the edge remains. There is also some shrinkage of the highly elongated configurations.

Using the island diagnostic solver reported earlier[1] we have also searched for the effects of the interaction of large-scale islands (m=2) with the high ripple region near the plasma edge.

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COMPARISON OF EXPERIMENTAL AND NUMERICAL FRC EQUILIBRIA*

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A field-reversed configuration (FRC) is an elongated compact toroid generated without toroidal field in a field-reversed theta pinch. Two-dimensional MHD FRC equilibria were previously computed inside an infinitely long cylindrical flux conserver[1]. We have extended this work to the actual coil geometry of the FRX-C device for comparison with the most complete experimental data[2] (20 mTorr fill pressure). A diagnostic code is used to compute the excluded-flux-radius profiles $r_{\Delta\phi}(z)$ and the interferometry profiles $\int n d\ell(r,z)$, assuming that the plasma is isothermal so that density and pressure contours are identical. The $r_{\Delta\phi}$ profiles approximate the shape of the FRC separatrix, while the $\int n d\ell$ profiles provide additional qualitative information on the structure inside the separatrix.

Equilibria have been obtained that match fairly well the roughly elliptical experimental separatrices for pressures on the separatrix β_s greater than about 0.5. The best fit to the experimental $r_{\Delta\Phi}$ data is obtained for $\beta_s \sim 0.6$, in good agreement with an independent estimate of β_s from side-on interferometry[2]. The numerical equilibria have an average pressure inside the separatrix larger than $1-x_s{}^2/2$. This observation (which is consistent with the experimental data) is shown to be due to the passive end-mirrors that confine the FRCs of interest. A comparison of the numerical $\int n d\ell(z)$ profile for the $\beta_s = 0.6$ case with the experimental $\int n d\ell(z)$ profile suggests that the inner flux surfaces in the experiment are more elliptical than those obtained numerically. A somewhat closer agreement with the experimental data is obtained with equilibria that have a $p(\psi)$ that is more peaked at the field null. To match the experimental data $p(\psi)$ must be peaked so much that the resulting equilibria are m=0 tearing mode unstable.

* This work was performed under the auspices of USDOE.

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THE ROTATIONAL INSTABILITY IN FIELD-REVERSED CONFIGURATIONS*

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Previous work on the rotational instability in FRCs has been based on the MHD model applied to a nearly circular plasma.[1] A simple argument based on Bernoulli's law can be used to show that the total pressure on the edge of the rotating FRC is given by an expression of the form $p + B^2/2 \propto (\text{const}-u^2/2)$.[2] Now, this pressure must be balanced by the magnetic pressure on the other side of the interface. Hence, where the external magnetic pressure is low, the fluid speed must be high, and vice versa. But the fluid velocity will be low where the surface bulges out and high where it bulges in (think about two-dimensional flow around outward- and inward-pointing corners), so the following general statement can be made: A rotating FRC equilibrium that excludes a multipole field such that multipole field nulls occur on the fluid-vacuum interface must bulge out where the external magnetic pressure is high and bulge in at the field null. This is just the opposite of what is observed in experiments and simulations where the plasma surface is caved in where the multipole field is high. The only way for such a state to be achieved in the sharp-boundary model is for the field nulls to disappear and to be replaced by cusps. This means that the plasma surface is not at all circular, and stability arguments based on a circular approximation may be in error. In particular, the result of Ref. 1 that for an elliptical deformation being opposed by quadrupole fields there is essentially no stabilization probably does not apply to experiments, since this result depends on special features of the circular approximation. Hybrid simulations, on the other hand, do show quadrupole stabilization of the n=2 rotational mode together with large deformations of the plasma surface that could be interpreted as an approach to a cusp-like equilibrium.[2] However, the multipole field strengths required in the simulations to give stability are a factor of 2-4 higher than the experimentally observed thresholds. To study the possibility that this discrepancy is due to a retardation of the plasma spin-up caused by early application of the multipole fields, for which there is some experimental evidence,[3] a two-fluid simulation code has been written. Preliminary results from this study will be discussed.

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INSTABILITIES EXCITED BY AN ENERGETIC ION BEAM AND ELECTRON TEMPERATURE ANISOTROPY IN TANDEM MIRRORS*

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The theory of cross-field ion streaming instabilities is applied to the parameter regime of the end cells of the upgraded Tandem Mirror Experiment with neutral beam injection. The cross-field ion drift as well as the electron thermal anisotropy $T_{e\perp} > T_{e||}$ provide the free-energy which drives the instabilities. Three instabilities have been found. A nearly perpendicular propagating modified two-stream like instability, an obliquely propagating ion-ion streaming instability and an obliquely propagating kinetic cross-field streaming instability have been identified. The first two waves are electrostatic and have the largest growth rate. For the actual operation conditions of the Tandem Mirror Experiment, it is found that the ion-ion streaming instability may have the largest growth rate. When more energetic neutral beams become available, the two-stream like instability may play the dominant role in the stability of these devices.

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SHERWOOD THEORY MEETING 1984

April 11 to 13

HAMILTONIAN STUDIES OF COMPRESSIBLE REDUCED MHD*

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Compressible high beta reduced MHD (CRMHD) is a system for modelling tokamak discharges.[1] CRMHD has four field variables (pressure, poloidal flux, scalar vorticity and parallel flow) that appear in the equations in the form of quadratic Poisson-bracket-type nonlinearities; its linearization is in accurate agreement with non-reduced MHD at large aspect ratio. CRMHD is simple enough to be integrated by conventional numerical techniques.

We show that CRMHD is a Hamiltonian field theory by presenting its generalized Poisson bracket (GPB).[2] GPB's possess the Lie-algebraic properties of conventional Poisson brackets. Together with a Hamiltonian, they produce the equations of motion in Hamiltonian form. Unlike conventional Poisson brackets, GPB's possess a special class of constants, called Casimirs, that can be used to construct the variational principle for equilibrium. This formulation explains how variational principles, such as those involving $\underline{A}\cdot\underline{B}$, are connected with the dynamical equations. Equilibrium variational principles are formally shown to be fixed points of the appropriate Hamiltonian. For CRMHD, the variational principle produces equilibria with poloidal and toroidal flow as well as pressure. A general prescription for determining the stability of these equilibria is discussed.[3] In the case of CRMHD, a restriction on the toroidal current profile is obtained.

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2R13

COMPUTER SIMULATION OF RF STABILIZATION OF THE FLUTE INSTABILITY

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ABSTRACT : Stabilization of a mirror confined plasma by RF fields is simulated using a 2 1/2-D electromagnetic relativistic particle code (the EBT code[1]). Magnetic field and density gradients are set up such that the flute instability occurs without RF. We explore stabilization for frequencies near the ion cyclotron frequency; the imposed electric field is perpendicular to the static magnetic field.

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Poloidal Flux In Stellarators and Torsatrons *

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Stellarator devices operate considerably differently than tokamak devices, in that rotational transform appears only when a modulation of the toroidal field appears in concert with a modulation of the poloidal field. Tokamaks only require a constant or nearly constant poloidal field to produce a net transform. The basic reason for this difference is that no net current is required for stellarator operation, so no net poloidal field component can be generated.

Torsatrons and stellarators produce the transform in the same way. The stellarator has identical helical coils in which currents flow in opposite directions. As a result, no net vertical field appears at the location of the magnetic axis, and no external compensating vertical field is needed. However, torsatron devices have helical coils in which the currents flow in the same direction. This results in the presence of a net vertical field at most locations. To locate a magnetic axis in a desired location, an external vertical field is usually required to cancel the vertical field produced by the helical coils.

Compensation of the vertical field in the case of a torsatron, or the lack of a vertical field in the stellarator itself, may not necessarily result in a zero vertical or poloidal flux. The purpose of this calculation is to determine and compare the poloidal flux in stellarator and torsatron devices. The existence or absence of flux is important in the case of time varying fields, since a net ohmic current could flow in the plasma if the flux is non-zero.

Poloidal (vertical flux in the z=0 plane) flux has been calculated for the Proto-Cleo stellarator and the Proto-Cleo torsatron from the major axis to the magnetic axis by integration over a series of concentric rings. The intersection of magnetic surfaces with the z=0 plane is then determined and flux from the magnetic axis outward can then be computed.

The integrated poloidal flux on the axis of the stellarator is identically zero. The flux then monotonically increases from the axis outward so that the rotational transform can be defined as

$$\iota = \frac{d\psi_p}{d\psi_T} ,$$

where $d\psi_p$ is the poloidal flux change between surfaces. $d\psi_T$ is the corresponding toroidal flux change.

In the case of the torsatron, the flux rapidly increases from the magnetic axis outward to the helical coils. In crossing the helical coils, the flux increases slowly to the magnetic axis and then decreases slowly to the outer helical coils. Outside of the helical coils, the flux rapidly drops through zero and then returns to zero at infinity. The magnitude of the poloidal flux is more than three orders of magnitude higher in the torsatron than in the stellarator. Hence, ohmic currents are not normally observed in stellarators, but are regularly seen in torsatrons, when the fields change in time.

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A Model Distribution Function for Thermal Barrier Electrons*

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We present a new analytic form for the electron distribution function in the end plugs of thermal barrier tandem mirrors. The model includes cold, warm and hot electrons, characterized by velocity-space regions in which either strong ECRH or isotropization due to Coulomb scattering dominates. No arbitrary high energy cutoff is imposed. The model allows one to analytically calculate the local electron density as a function of magnetic field and electrostatic potential. Conversely, the barrier potential drop and ion-confining potential can be obtained in terms of the ion density profile in the end cell. Results are similar to the earlier "strong RF" model,[1,2] with the barrier depth varying as the logarithm of the mirror-to-barrier density ratio and the peak-to-barrier potential varying as the 2/3 power of the peak-to-barrier density ratio.

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Ion Cyclotron Resonance Heating by Means of the Fast Wave in a Longitudinally Inhomogeneous Magnetic Field

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We consider the coupling between the fast wave and the slow ion cyclotron wave in a plasma in which the equilibrium magnetic field is longitudinally inhomogeneous. Such a coupling can only occur when a second ion species is present and for finite $k_\perp$. This configuration is of relevance to mirrors and also tokamaks. An approximate dispersion relation is obtained from the usual cold plasma model by replacing all slowly varying quantities by their value at the resonance. The resulting equation preserves the cut-off properties of the original equation. The approximate dispersion relation is then used to analyse the mode conversion of the fast wave to the slow wave at the minority resonance. For $c_A^2k_\perp^2/\omega^2 \ll 1$ the transmission coefficient agrees with the result previously obtained by White et al [1]. As $c_A^2k_\perp^2/\omega^2 \to 1$ the transmission vanishes and for incidence from the weaker field region total absorption occurs. When the wave is incident from the stronger field region the maximum absorption as a function of the minority fraction and $k_\perp$ is 25%. For $c_A^2k_\perp^2/\omega^2 > 1$ one of the propagating waves disappears and there is no longer any coupling. The behaviour for $c_A^2k_\perp^2/\omega^2 \gtrsim 1$ is in contrast to that found by White et al [1] who predicted complete transmission for large values of their coupling parameter.

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TRANSPORT SIMULATIONS OF THE PDX/ASDEX H-MODE*

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The BALDUR transport code has been used to simulate PDX and ASDEX H-mode plasmas for which auxiliary heating is accompanied by up to a factor of two increase in the energy confinement time. The BALDUR code solves time-dependent radial diffusion equations to simulate the evolution of the current and particle densities and the electron and ion temperatures.

A semiempirical transport model constrained by global confinement scalings and containing profile factors was found to reproduce many of the essential features of plasma confinement in the ohmic heating, low- and high-confinement phases of typical plasma discharges.

The effects of oxygen and iron impurities and of a simple edge model for divertors which incorporates recycling have been included. The simulations are compared to experimental results.

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2R18

ICRF CATALYZED FUSION REACTIVITY ENHANCEMENT*

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Fusion product slowing down distributions can be altered by the presence of ICRF microwaves; at high energy the RF velocity diffusion competes with collisional slowing down. We are interested in the marginally stable saturated state in which the fusion product distribution supports an ion cyclotron wave which damps on the background bulk ion distribution. The question of whether bulk species fusion reactivity is significantly changed by the increased ion-ion coupling is examined.

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Efficiency Limit for Current Drive by Fast Waves*

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The efficiency of current drive by fast waves is limited by relativistic effects.[1] However that calculation made use of an electron-electron collision operator which did not conserve momentum. While this is usually of little consequence for current drive by fast waves, it may be important in the relativistic regime since the momentum per unit current is large. Here we investigate this possibility.

We start with the full relativistic collision operator.[2] Retaining only the Coulomb part of the binary interaction, the operator reduces to the Landau form[3]

$$C(f_a, f_b) \propto \frac{\partial}{\partial p_i} \int Q_{ij}(v - v') \left(\frac{\partial f_a}{\partial p_j} f_b' - \frac{\partial f_b'}{\partial p_j'} f_a\right) d^3p', \quad Q_{ij}(v) = \frac{v^2 \delta_{ij} - v_i v_j}{v^3}$$

(f_a is the test species, f_b is the background). As such it conserves mass, momentum, and energy and has the relativistic Maxwellian as its steady state. In order to study the problem of steady-state current drive, some way must be found of extracting energy to balance the input of rf energy. This is done by the approximation

$$C(f_e, f_e) = C(f_e, f_{eM}) + C(f_{eM}, f_{e1})$$

where f_{eM} is a Maxwellian and F_{en} is the n'th Legendre component of f_e. Omitting the term $C(f_{eM}, f_{e0})$ is equivalent to postulating a heat sink that negates the bulk heating effect of the resonant electrons. As desired, this operator conserves momentum. It gives the Spitzer-Harm conductivity[4] in the non-relativistic limit.

In order to evaluate this collision operator, the Rosenbluth potentials[5] are generalized to include relativistic corrections. When determining current-drive efficiencies in a hot plasma, use of this operator indicates a potentially important 20-30% increase over previous estimates.[1] The momentum conserving nature of this collision operator also means that it may be used in non-relativistic situations where an electric field is present, for instance, in rf start-up experiments.

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A SIMPLE MODEL FOR LOWER HYBRID CURRENT DRIVE IN TOKAMAKS*

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One problem associated with the theoretical understanding of lower hybrid current drive in tokamaks is the inability of the $N_{||}$ spectrum predicted by Brambilla theory to couple with any significant number of electrons. Some $N_{||}$ modification mechanism must be invoked to explain the successful current drive experiments on such devices as PLT and Alcator. One possible candidate is the non-conservation of the poloidal wave number associated with toroidal effects. However, this necessitates a relatively complex model involving toroidal geometry and many passes through the plasma by the rays.

An alternative mechanism, which we utilize here, is the combination of scattering and shear effects to broaden the initial $N_{||}$ spectrum. Without scattering, the $\vec{k}_\perp$ of the wave would be always in the radial direction; scattering produces a non-zero component in the poloidal direction which shear then converts into a change in $N_{||}$. These effects can be predicted using scattering theory[1].

We take advantage of this process to produce a simple straight-cylinder, single pass, one velocity dimension model for the current drive. The Fokker-Planck equation can be analytically solved under this assumption and the current driven can be easily found.

Initial results seem in reasonable agreement with experiment; for PLT-like parameters about $300 rmkA$ of current is driven by 200 kW of power, and for Alcator parameters we find $N_{||}$ spectra in the interior of the plasma similar to those observed[2].

Only a small amount of scattering is required for absorption of a significant portion of the incident power as once a small part of the energy migrates to higher $N_{||}$ quasi-linear flattening will bring large numbers of electrons into resonance with the bulk of the wave energy. However, the current driven can still have a relatively strong dependence on the plasma parameters and the wave-guide phasing as the efficency of current drive is a function of the resonant electron energy.

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*Work supported by U.S. DOE Contract DE-AT03-84ER53158.

BALLOONING INSTABILITIES AS THE CAUSE OF H_α SPIKES?*

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During high power neutral beam heating of divertor tokamak plasmas (ASDEX, D-III, PDX), the plasma can be made to change from an L-mode to an H-mode of operation, which has better energy confinement.[1] In turn, the energy confinement in the H-mode of operation is limited by the appearance[2] of "H_α spikes," which are repetitive (~ 1 msec), short time scale bursts of light due to coolings of the plasma just inside the divertor separatrix. The plasma pressure profile in these discharges is relatively flat out to the divertor separatrix, but falls off very rapidly (e-folding distance of a few cm) outside the divertor separatrix.[2] We hypothesize that the H_α spikes are due to ballooning instabilities near the separatrix. Ballooning instabilities are possible because, although the β is low near the separatrix, the pressure gradient is sufficiently steep that the instability criterion $dp/dr > (B^2/2\mu_0)R_0/\ell_c^2$ can be satisfied there. The effective connection length ℓ_c must be determined from an eigenfunction solution that takes account of the two-dimensional nature of the divertor x-points, which acts to localize the mode near the outer side of the torus. Also, the magnetic field perturbations involved in the ballooning modes can change the magnetic topology near the divertor x-points.

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* Work supported by the Office of Fusion Energy, U.S. Department of Energy under contract DE-AC02-80ER53104.
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Analysis of Localized Interchange Modes in PDX*

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Tokamaks are known to operate with safety-factor less than unity on axis as evidenced by sawteeth oscillations. Ideal MHD theory would predict various possible instabilities in this situation. For example the $n = 1$ internal kink mode is unstable when the $q = 1$ surface lies in the plasma and the plasma pressure exceeds some critical value. This mode has in fact been observed and its dynamical interaction with the fast ion component due to neutral beam injection has been identified as the "fishbone oscillations" in PDX. In addition to this instability, with $q_{axis} < 1$, we might even expect high-m localized modes. Generally these modes require a rational surface in the region near the axis with $q < 1$. They are however easily stabilized bny removing the pressure gradient in the small unstable region. Consequently we do not expect this mode to have disastrous effects on the plasma.

Experimentally we have observed MHD activity in the central region of PDX, which can be identified as high-m internal modes. They have characteristic poloidal and toroidal mode numbers in the range 4-10. We have analyzed these discharges with the PEST code and show that these modes are indeed likely to be high-m/n localized interchange modes. Detailed results of the theoretical analysis will be prescribed.

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Determination of Multiple Tokamak Equilibria

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Two algorithms for exploring fixed and free boundary, axisymmetric bifurcations of a tokamak plasma with the PEST equilibrium code will be presented. One is computational and is based upon constraining the solution in each iteration; the other is semi-analytical and is based upon bifurcation theory. These will permit the results to be checked against each other in a neighborhood of a critical point. For fixed boundary, the equilibrium manifolds of a rectangular or elliptical cross-section plasma can be derived analytically. A computational method will be presented for general boundaries. A first assault upon the analysis of 3-D equilibria without or with multiple magnetic axes will be indicated.

OPTIMUM STABILITY LIMITS OF BEAN SHAPED PLASMAS

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ABSTRACT

Previous studies on shaping of the poloidal cross section of tokamak configurations have shown that the beta limit with respect to ballooning modes can be greatly enhanced by indenting the inner side of the torus [1]. It was further found that the stability envelope and the existence of and access to the second stable region varies widely with geometry and equilibrium plasma profiles. We present the results of a study where the pressure profiles are chosen to optimize the region of stability and, in some cases, the q profiles are consistent with ohmic heating. The procedure for optimizing the pressure profile consists of solving the infinite - n ballooning mode equation locally on a flux surface for the critical pressure gradient at which the equilibrium is marginally stable, and integrating the result over the plasma cross section to obtain the optimum pressure profile. The specification of the steady state ohmic q profile is obtained by demanding constant $\langle \underline{E} \cdot \underline{B} \rangle / \langle \underline{B} \cdot \nabla\phi \rangle$ throughout the plasma. The equilibrium, ohmic q, and ballooning equations are iterated to achieve self-consistency. Results show that the critical indentation needed to reach the second stable region is significantly lower than previously calculated. In one case the critical indentation, d/2a, is lowered from 0.32 with an analytic pressure profile, to 0.20 with the optimized pressure profile. In another case, where previously no second stable region existed with a standard analytic pressure profile, a second stable region is recovered with the optimized pressure profile.

We also present results of a stability analysis in the PBX experimental parameter space. Preliminary indications are that for typical PBX parameters, a second stability region exists and is accessible with $d/2a \lesssim 0.3$. It is also found that elongation is undesirable for the second region accessibility, in contrast to the first region beta limit elongation dependence. Finally, we present stability results for inverted (with respect to the major axis) bean tokamaks and bean shaped RFP's.

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CUBIC TURBULENCE IN FUSION PLASMAS

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The interaction of a high frequency wave with itself leads to cubically nonlinear partial differential equations. In order to test statistical theories of such equations, we consider the cubically nonlinear Schrödinger equation model of strong Langmuir turbulence.[1,2] This model contains the modulational instability and soliton formation, but is less complete than the Zakharov equations[3,4] which contain the parametric decay instability. To begin a statistical study of this equation, we consider first the three mode truncation.[5,6] Applying the cubic direction interaction approximation[7,8] to the undriven, undamped case, we find analytically that a steady state solution exists with each correlation function equal to the same constant times the corresponding response function. For a general initial value ensemble, we prove analytically that the above steady state cannot be reached. Rather, we find numerically that the statistical theory evolves to a state of equipartition (equal energy in each of the three modes) which is not a steady state.

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Approximate Flux Conserving Stellarator*

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A steady state stellarator equilibrium is usually assumed to have zero current inside each flux surface. In this limit, the rotational transform profile changes strongly with increasing beta. The transform at the magnetic axis increases with beta, while the transform at the edge decreases. This results in double valued profiles even for moderate beta values ($\beta \geq 3\%$). Such profiles can be unstable. Therefore, it is desirable to control the transform profile in going to a high beta regime. This can be achieved by conveniently shaping the poloidal magnetic field. Using the stellarator expansion,[1] we calculate sequences of zero current equilibria with approximately constant rotational transform profile. We also investigate the stability properties of these equilibria. We show that for the ATF device[2] such equilibrium sequences can be obtained using the present vertical field coil system to shape the poloidal magnetic field. This mode of operation offers a better way of accessing the second stability regime.[3]

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EFFECTS OF COLD GAS ON THE OPERATION OF A TANDEM MIRROR*

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Warm ions trapped in the transition region and thermal barrier of a tandem mirror must be pumped out to maintain the low trapped ion densities necessary for successful operation. The sources of these warm ions are trapping of passing ions from the central cell due to collisions and ionization and charge exchange of cold background gas. To pump out these trapped ions, neutral beam pumping and/or drift pumping[1] will be employed. We have used a multi-region Fokker-Planck code[2] to study the ion pumping requirement and the effect of cold gas in MFTF-B and TMX-U. Ionization and charge exchange of the background gas provide the source of cold trapped ions while charge exchange also results in a loss of warm plasma ions. The effects of attenuation of the cold background gas by the plasma are included in defining the effective cold ion source strength. Initial results indicate that the cold gas increases the amount of neutral beam or drift pumping that will be required to maintain the low warm ion density required in the MFTF-B anchor. Detailed results of both TMX-U and MFTF-B will be reported.

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STABILITY OF THE RADIAL ELECTRIC FIELD IN A NONAXISYMMETRIC TORUS*

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The particle fluxes in nonaxisymmetric tori (ripple tokamaks, stellarators, and EBTs) are not intrinsically ambipolar, i.e., they explicitly depend on the radial electric field. The ambipolar radial electric field has to be determined self consistently from the Maxwell and transport equations. When the electric field has relaxed to the state where the quasineutrality condition $\Gamma_i = \Gamma_e$ is roughly satisfied, the quasineutrality condition can yield multiple values of the radial electric field for some plasma parameters. Some of these roots are stable. The stability properties of the radial electric field are studied here from the thermodynamic point of view. Accordingly, the stable values of the radial electric field are the local minima of a potential — the generalized entropy production rate. In deterministic cases, the value of the radial electric field is dependent upon the initial plasma parameters and hysteresis-like behavior occurs. However, if fluctuations are taken into account, depending on their size, the value of the radial electric field can be either at the absolute minimum of the potential or it can still exhibit hysteresis-like behavior.

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VARIATIONAL METHOD FOR TOROIDAL EQUILIBRIA WITH IMPERFECT FLUX SURFACES

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A variational spectral method is developed for toroidal equilibria with imperfect flux surfaces. The magnetic field is represented in a form (due to Boozer[1]) which is predicated on the existence of a neighbouring field with perfect surfaces. Equilibria are defined by the mapping between two coordinate systems: the cylindrical system (R,ϕ, Z) and the "magnetic" system (v,θ,ζ), where v is an appropriate radial label for the neighbouring field, and θ and ζ are respectively the poloidal and toroidal angles parameterising a given constant-v surface. Two types of mapping, namely, the inverse mapping $(v,\theta,\zeta) \rightarrow (R,\phi, Z)$ and the mixed mapping $(v,\theta,\phi) \rightarrow (R,\zeta, Z)$ are considered. The dependent variables are Fourier-analysed in θ and ζ (or ϕ), and a set of ordinary differential equations are derived for the amplitudes in v from the variational principle. Given that several variational spectral codes for three-dimensional toroidal equilibria with perfect surfaces already exist[2], it is argued that the present method may be implemented without much difficulty.

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EFFECTS OF HELICAL FIELDS ON REVERSED FIELD PINCH

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The OHTE configuration utilizes helical windings to aid the pitch reversal of the reversed field pinch (RFP) configuration. To assess the effect of helical winding on stability properties, low frequency modes ($\omega << \Omega_i$) in straight helical geometry are studied by using ballooning transformation. OHTE and RFP equilibria with the same functional forms of pressure and paramagnetic current flux are generated numerically and compared. It is found that helical field introduces three essential effects:

(1) Enhancement of global magnetic shear near the separatrix.
(2) Modulation of local shear within the flux surface.
(3) Geodesic curvature.

The first effect is stabilizing whereas the other two are destabilizing. Depending on the functional form of pressure and paramagnetic current profiles, the overall effect of helical field varies from weakly to strongly stabilizing for high conductivity ($E_{\parallel} = 0$) modes. Examples will be shown.

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MODELS OF ENERGY CONFINEMENT IN TOKAMAKS*

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Numerous experiments on beam-heated tokamaks have shown that energy confinement time decreases with increasing beam power and increases with increasing plasma current.[1] This behavior has been approximately reproduced by Connor, Taylor, and Turner[2] with a transport model in which a constant INTOR thermal conductivity is increased near the plasma edge by marginally stable, ideal ballooning modes and near the plasma center by sawtooth oscillations associated wih $m=1$ modes. Using the ONETWO plasma transport code[3] we have extended the treatment of Connor, Taylor, and Turner to include more general heating and density profiles; separate, temperature-dependent models for electron and ion energy transport; and effects of noncircular plasma cross sections. Our calculations show, for example, that the confinement degradation becomes much worse as the density profile becomes more peaked. However, this profile dependence as well as the dependence on limiter q (arising from the central $q \simeq 1$ constraint due to sawtooth oscillations) can be incorporated into a single scaling relation for the energy confinement time τ by appropriately defining variables. Thus $\tau/\tau_{OH} = (\tau_{OH}/\tau_{opt})^{-\delta}$, where τ_{OH} is the ohmic confinement time, and τ_{opt} is the confinement time at optimum beta. The exponent δ varies from 0 at low power (when $\tau_{OH}/\tau_{opt} \leq 1/2$) to 1 at higher power (when $\tau_{OH}/\tau_{opt} \geq 2$) and depends only weakly on the density profile and limiter q. Calculations showing the variation in energy confinement time with power, current, density, and plasma shape are presented for various model assumptions and compared wih experimental results.

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Ideal magnetohydrodynamic equilibrium and stability studies of a toroidal system with arbitrary helical fields

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This work is primarily motivated by the promising aspects of the stellarator configuration. Recent results suggest that a toroidal device with helical fields may have some advantages compared to axisymmetric devices, i.e., tokamaks, with regard to controlling disruptions. The present work is a generalization of previous work[(1)] which was restricted to one type of helical field (one ℓ-number, ℓ being the azimuthal multipolarity), and no vertical field. We have now been able to generalize this to include any combination of helical fields and also an arbitrary vertical field. This applies both to the equilibrium and the stability analysis.

The study is restricted to the surface current model, where we assume all the current to be flowing in a thin sheath forming the boundary between plasma and vacuum. From previous experience such a model gives a reasonable description of the equilibrium and the stability properties of the global modes in such systems.

The main part of this work is analytic, and we resort to numerical solutions only at the final step both in the equilibrium part and the stability part. The stability analysis is based on the MHD-energy principle, which we are able to write in a concise form suitable for numerical evaluation in the final step.

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Trapped Particle Destablization of The Internal Kink Mode*

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The internal kink mode is destabilized by trapped high energy particles, leading to a new branch of the internal kink dispersion relation with a growth rate near the ideal magnetohydrodynamic value, but with a real frequency near the trapped particle precession frequency.[1] This kinetic branch of the dispersion relation is investigated numerically for a variety of particle distributions. Mode growth rate and frequency is found as a function of plasma β, density, and trapped particle energy and distribution. Relevance for the occurance of the fishbone instability [2] for various plasma heating schemes is discussed.

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Lagrangian and Hamiltonian Theory of Gyrokinetic Equations

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Gyrokinetic equations have an essentially elementary structure and function, and yet they are notorious for the amount of algebra required for their derivation and manipulation. Nevertheless, a little attention to the general principles involved in gyrokinetic equations shows that many of the steps in their derivation can be completely bypassed, while others can be greatly simplified.

This is true even if one chooses not to use a Hamiltonian formalism. However, even further benefits are realized by the use of a Lagrangian and Hamiltonian formulation of the characteristic orbits in phase space. Field Lagrangian methods promise to go even further, by providing a variational formulation of the equations of self-consistency.

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CTR: Controlled or Catastrophic Thermonuclear Reactors?

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Ashworth has discounted seven of the eight proposed advantages for Controlled Thermonuclear Reactors (CTR).[1] Regarding the claims of "Inherent Safety, No Runaway" he does not discuss the claim of "No Runaway". Consider a large multi-mirrored device and the question of thermal runaway on ignition of DT. The first thermal excursion occurs rather quickly and T_i may rise to 150 keV from the roughly 10 keV ignition temperature. The plasma beta then will rise by 15-fold unless there is a drastic loss of plasma. Outgassing and desorption of D and T from the loaded walls will occur to a major degree and lead to a second thermal and/or power excursion. The overall increase in T and/or β as a direct result of the strong power excursion ($p \propto n^2\langle \sigma v\rangle \propto \beta^2\langle \sigma v\rangle/T^2$) may result in plasma collapse into the hottest mirror cell in the form of a high beta reversed field configuration (RFC). Should this RFC take on aspects of the Ion-Layer, Electron-Core plasma[2], the ExB drive of ions will give collisional energies proportional to the nuclear <u>masses</u> ($E^* \propto Mc^2E^2/2B^2$) at the negative core. The EBT, Leningrad ALPHA, and carbon arc plasmas have all demonstrated hot ions with the core of the plasma of order 100 volts negative. In the energetic carbon arc the ions were 100 times hotter than the electrons ($T_i \propto 100Te \propto 500$ eV), due in part to a process called Excitation-Heating.[3] In a D-D-T fusion reactor the multi-MeV fusion products may lead to possibly hundreds of kilovolt negative plasma potential at the core. The questions of nuclear Excitation-Heating and of nitrogen or oxygen ignition (due to accidental leakage into the plasma) merit serious study.[4] An equilibrium configuration, analogous to ball lightning, may develop wherein the poloidal and toroidal currents are balanced by the Lorentz force and the excess pressure,[5] independent of the applied magnetic field. As a safety measure it is suggested that nuclear stable krypton gas be available to quench any such Catastrophic Thermonuclear Reactor incident, if such be possible.

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The Effect of Finite β on Stellarator Transport*

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Recent work[1] has shown that stellarator transport is quite sensitive to the precise harmonic decomposition of the magnetic field strength B. This decomposition is, in turn, quite sensitive to the plasma β. Thus, a stellarator whose vacuum fields are transport optimized can have over an order magnitude poorer confinement when near its equilibrium β limit.

Using analytic theories of equilibrium[3,4] and "$1/\nu$" stellarator transport,[1,2] we develop a theory of the dependence of stellarator transport on β, and apply it to various stellarator configurations of interest. The effect is quite important for most circular-axis stellarators, which have small rotational transform per field period ι/N. Devices with large ι/N (e.g. heliac), are less affected by this mechanism (though they may be more sensitive to loss of surfaces from changes in β [4]). The theory permits one to determine the vacuum fields desired to optimize transport at a prescribed β. The effect of an external vertical field is also considered.

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TOROIDAL SHEAR ALFVÉN INSTABILITY DUE TO ENERGETIC PARTICLES*

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In the recent neutral beam injection experiments in PDX and PLT, high frequency ($f \sim 100$ kHz) oscillations have been observed on Mirnov and x-ray detectors and cause neutron emissivity to drop. In PDX these high frequency oscillations are dominantly $m = 5$ with phase velocity in the ion diamagnetic drift direction. To explain these high frequency oscillations we propose the toroidal shear Alfvén waves which are induced by nonuniform toroidal field and are destabilized by resonanting with energetic ions through magnetic drift resonances. In terms of the high-n ballooning mode formalism, we have analyzed the toroidal shear Alfvén wave from the ideal MHD theory. The toroidal shear Alfvén wave has also been confirmed by the PEST code for low-n modes. When energetic ions are taken into account, the toroidal shear Alfvén wave becomes unstable with the growth rate increasing and real frequency decreasing with increasing energetic ion density. For typical PDX L-mode operational parameters near $q = 1$ surface, our results show that the maximum growth rate occurs at $m \approx 5 \sim 6$ with $\gamma/\omega_A = 0.1$ and $\omega/\omega_A = -0.2$ ($f \approx 120$ kHz). These results which are consistent with the experimental observations, suggest that the high frequency oscillations observed in the PDX and PLT neutral beam experiments are caused by the toroidal shear Alfvén eigenmodes.

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Theory of Weakly Collisional Kinetic Alfvén Waves in Sheared Magnetic Fields*

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The stability and spectra of the weakly collisional kinetic Alfvén waves in a sheared slab geometry are investigated. The effects of finite ion gyroradius and diamagnetic drift frequencies are included simultaneously. First, we present an analytical proof of the non-existence of unstable eigenmodes. The eigenfrequencies of the damped modes are then derived analytically via asymptotic analyses. The dispersion relation recovers the various limiting cases[1-3] previously studied. In particular, we find that, due to the finite Larmor radius effects, the damped mode asymptotically approaches a finite real frequency as the resistivity reduces.

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Nonlinear Evolution of Tearing Modes in Cylindrical Plasmas

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ABSTRACT

Nonlinear behavior of a single tearing mode in a cylindrical plasma is studied, using visco-resistive MHD equations with Tokamak scaling. The nonlinear evolution of the mode amplitude can be obtained from two sets of linear equations in which the time variable t acts as a parameter. It is shown that when the mode amplitude $A(t)$ is much greater than $\eta^{2/3}$, the mode grows algebraically just as in the case of a slab plasma. Transition from the exponential growth to the algebraic growth is also described.

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EFFECT OF RADIAL STRUCTURE OF ELECTROSTATIC OR MAGNETIC PERTURBATIONS ON THE DIFFUSION OF TEST PARTICLES IN A SHEARED MAGNETIC FIELD

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Test particle motion in a sheared magnetic is known to be truly stochastic if the amplitudes of electrostatic or magnetic perturbations ψ_{mn} are large enough (resonance overlap condition). Conventionally the radial mode structure is ignored, which leads to a discrete model. We show that while for m=1 (Taylor-Shirikov or standard model) strong deviations from quasi-linear theory appear, superposition of only 2 or 3 different m already leads to an almost perfect quasi-linear behaviour. Assuming a Gaussian mode structure $\psi_{mn}(x) \propto \exp\{-\kappa^2(x-x_{mn})^2\}$ we find (for m=1) that $D \propto \langle|\psi_{mn}|^2\rangle$, where $\langle\ \rangle$ is the radial average taken over Δ_{mn}, the distance between neighboring resonant surfaces. For $\kappa\Delta_{mn}<1$ diffusion is as in the standard model ($\kappa \to \infty$), while for $\kappa\Delta_{mn} > 2 - 3$ it is practically quenched, independently of ψ. As a result antimetric or odd modes contribute far less to D than symmetric modes. Alternate radial shape functions as well as finite mode frequencies ω_{mn} were also investigated. One always finds $D \propto \psi^2$ for large ψ, no saturation due to finite radial mode extent is observed contrary to earlier predictions.

NONLINEAR SATURATION OF THE HOT ELECTRON INTERCHANGE MODE*

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Recent theoretical investigations of the high frequency hot electron interchange mode predict the onset of instability when the hot electron-to-ion density ratio exceeds a critical value.[1] This hot electron instability, whose frequency is $\gtrsim$ the ion gyrofrequency, was observed recently near the T-M transition in EBT.[2] In this work we study the nonlinear saturation of this mode. We use a renormalized nonlinear gyrokinetic equation for the hot electrons, and cold fluid equations for the ambient ions and electrons. The analysis is done in a slab model in a local approximation. The mode coupling comes from the nonlinear terms in the electron E x B drifts and from the convective derivative in the ion inertial term. Estimates for the saturated mode amplitude, the density fluctuation level, the particle transport, and the thermal conductivity are obtained.

*This work was supported by the U.S. Department of Energy.

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SHERWOOD THEORY MEETING 1984

April 11 to 13

PLASMA INJECTION ACROSS TRANSVERSE AND CURVED MAGNETIC FIELDS*

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Particle simulation techniques are used to investigate the propagation properties of a charge neutral plasma beam across transverse and curved magnetic fields. Plasma injection into a magnetic confinement device in the transverse or tangential direction is a nontrivial problem because of $\vec{\nabla}B$ and curvature drifts and subsequent charge separation. Two-and-a-half dimensional electrostatic and electromagnetic particle codes have been employed in the investigation.

In the case of transverse injection we find that the plasma can penetrate through the magnetic field by separation of electrons and ions to produce $\vec{E}\times\vec{B}$ motion, if the dielectric constant of the beam, ε, is sufficiently large ($\varepsilon = 1 + \omega_{pi}^2/\Omega_i^2$). This is in agreement with Reference 1. Propagation is found to occur for both $\beta \gg 1$ and $\beta < 1$. When $\varepsilon < \sqrt{M/m}$, the beam fails to propagate through the field. In the case of tangential injection into a curved magnetic field we find that a portion of the beam follows the field lines, a later portion deflects in the opposite direction[2,3], and some propagates straight through. The respective amounts depend on the length of the beam and on the Alfvén velocity. These phenomena can be by curvature drift and $\vec{E}\times\vec{B}$ motion. Effects of the background plasma will be discussed.

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Numerical Simulation of Plasma Potential Control Operation of TMX-U*

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Active reduction of the radial electric field in MFTF-B below ambient levels is necessary in order to avoid the onset of collisionless stochastic transport. Reduction of the radial electric field in tandem mirror reactor designs is necessary in order to control the drive for rotational instabilities. One possible technique which can be used to control the radial electric field in tandem mirrors is the use of biased or floating segmented end plates. Recently, experiments have begun in TMX-U in which the effect of such end plates upon plasma confinement and the radial electric field are being studied. In this study we compare the data obtained in these experiments with numerical simulations generated using the radial-transport code TMT. In the simulations, the ability of the end plate technique to reduce the electric field is found to be sensitive to the level of electron radial transport and field alignment errors.

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Compressional Alfvén Wave for Heating and Current Drive in the Presence of α Particles*

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In reactor conditions, fusion α particles may interact strongly with radio-frequency waves which are for heating and current drive. This poses a serious constraint on the type of wave for current drive in reactor conditions. We re-examine heating and current drive by cavity modes of compressional waves ($\omega < \omega_{ci}$) using a kinetic cylindrical plasma model including transit time magnetic and Landau damping on both electrons and α particles. Our results show that transit time magnetic damping on α's will be substantial in comparison with that on electrons unless the phase velocity of the wave is chosen such that $\omega/k_\parallel > v_e \gg v_\alpha$ where v_e and v_α are thermal velocities of electrons and α particles. Thus, only a current drive scheme[1] with $k_\theta > k_\zeta$ (k_θ, k_ζ are poloidal and toroidal wave numbers) and $\omega/k_\parallel \gtrsim 3v_e$, is able to avoid substantial Alfvén resonance absorption[2] near the edge and α particle damping, in contrast with schemes[3,4,5] based on $k_\zeta > k_\theta$ and $\omega/k_\parallel \simeq 0.1\, v_e \simeq v_\alpha$.

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The Reliability of Initial Value MHD Calculations of Tokamak Disruptions*

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We have proposed the nonlinear coupling of resistive tearing modes as the mechanism for some Tokamak disruptions.[1] This is based primarily on initial value resistive MHD calculations performed with a finite difference grid in minor radius and Fourier series expansion in the poloidal and toroidal angles.[2] The calculations show that, for certain q-profiles, the nonlinear interaction of modes of different helicities leads to the rapid destabilization of other modes. The resulting effects and the timescale are consistent with the Tokamak disruption.

Recently Eastwood and Hopcraft[3] have disputed this basic numerical result. Using a copy of our code, RSF, they claim to have shown that "numerical effects play a significant role: computational results based on RSF and related codes must be regarded as suspect until independently confirmed". However, they have taken the calculation much further in time than is warranted by the conditions they imposed. They allow the calculation to run well into the turbulent phase with only 11 modes represented. Moreover, we show that the energy conservation test, as they perform it, is neither a necessary nor a sufficient condition for convergence.

We go beyond refuting their specific claim, however, and consider each source of numerical error, in turn. It has been widely recognized that this type of calculation pushes the numerical techniques near to their limits. Therefore we, and other authors, have been especially careful to verify that the results are reliable. In addition to convergence studies, we produce the same results with three different computer codes which include both implicit and mostly-explicit schemes, full and reduced MHD equations. We conclude that, while it is easy for the novice user to run these computer codes to produce erroneous results,[3] the results we have published, and in particular the basic nonlinear mode coupling mechanism, are reliable and survive all tests.

We do not dispute the portion of Ref. 3 in which an analytical linear stability analysis is presented. This exercise provides some guidelines which could contribute to improved understanding of the timestep which we obtain from other considerations.

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A Consistent Drift Kinetic Theory

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ABSTRACT

The usual drift kinetic theory for treating plasmas in strong but weakly nonuniform magnetic fields is carefully examined, and an inconsistency involving some missing first order terms in gyroradius is discovered. A consistent drift kinetic theory is therefore developed, based on a more systematic formulation to include all the first order terms. The final equation governing the distribution function averaged over the fast time scale, gyro-period, is then compared with that obtained from the usual formulation.

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ATOMIC PROCESSES AND ENERGY LOSS IN DIVERTED EDGE PLASMAS*

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The physical state of the edge plasma and the energy balance in cool divertor plasmas is modeled including the relevant atomic collision processes. The plasma fluid and neutral transport equations are solved for a simplified two chamber model of the scrape-off divertor regime including sources. It is found that the excited neutral species of atomic and molecular hydrogen play an important role in the low-temperature, high-density plasma. Recent bolometer and thermocouple measurements on PDX show that only 20-30% of the heating power hit the neutralizer plates in the divertor. We find that the dissociation of hydrogen molecules in a high recycling divertor can account for the missing plasma.

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MOTION OF CHARGED PARTICLES IN STOCHASTIC MAGNETIC FIELDS*

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A general theory of stochastic differential equations has been developed based on the method of Stratonovitch. Using this theory, closed equations for the mean and mean square of the output process (for example the velocity of the particle) are obtained from a linear stochastic differential equation. These equations are used to analyze the trajectory of a single electron moving in a uniform, cylindrically symmetric magnetic field which contains random fluctuations in magnitude with time. Near the center of symmetry of the magnetic field the fluctuations produce cross field diffusion of the particle. At greater distances, where the induced electric field becomes important, the mean square displacement of the particle increases exponentially with time. In addition, the mean energy increases exponentially with time (heating effect). Results for various fluctuation amplitudes and frequency spectra will be presented.

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NONLINEAR THEORY OF ELECTROMAGNETIC TRAPPED ELECTRON MODES*

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A theory of electromagnetic trapped electron modes in a circular cross-section tokamak is presented. We concentrate on the magnetic branch, rather than the more familiar electrostatic branch, and calculate linear growth rates using a variational principle. The nonlinear stage of the instability is studied using an essentially quasilinear theory to calculate the particle and thermal diffusivities. We show that, in contrast to the electrostatic modes,[1] the anomalous thermal conductivity for the magnetic modes can be large compared to the diffusion coefficient.

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MAGNETIC ISLANDS IN THREE-DIMENSIONAL TOROIDAL PLASMA*

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The production of magnetic islands by plasma pressure in three-dimensional toroidal plasma equilibria is analyzed. Far from the rational surfaces a procedure based on linearization in the plasma pressure applies. This yields the solution in terms of δ-function currents at the surfaces. These currents are found by a nonlinear analysis valid in the vicinity of the island. The result is a set of coupled nonlinear equations determining the island width. Scaling is found by using the approximation of nearly circular flux surfaces. The results indicate that the island size depends dramatically on whether a magnetic well is present. Generally, if a magnetic well is present, islands are insignificant. However, if a magnetic hill is present, islands always overlap for sufficiently large mode number for arbitrarily low pressure. These islands are the saturated state of resistive interchange modes. Implications for present and planned devices will be discussed.

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Formation of Magnetic Islands in Three-Dimensional MHD Equilibria*

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In fully three-dimensional, finite β MHD equilibria, resonant pressure driven currents cause magnetic island formation, even if the vacuum field has good flux surfaces. We have used an analytical expansion method to study the physics of this process, and to obtain some estimates of island widths. The resonant pressure driven currents are associated with a variation in $\oint d\ell/B$ on the rational surface. Even if $\oint d\ell/B$ is constant on the rational surfaces of the vacuum field, it is in general not constant on any rational surface of the finite β equilibrium. This is due to a broadening of the spectral width of the Jacobian with increasing β.

For stellarator equilibria, island formation decreases the aperture of the plasma with increasing β, and also gives an equilibrium β limit. As an application of our theory, we have calculated the equilibrium β limit for the heliac reference design.

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THEORY OF PLASMAS NEAR THE LAWSON LIMIT

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Experiments with record values of $n\tau_E$ carried out within the Alcator program have indicated, consistently with our earlier analysis and suggestion, that the plasma confinement properties can be improved considerably if the density profile can be made relatively peaked, as is possible to do by pellet injection [1].

This follows from noticing that, with the "flat" density profiles that can be "spontaneously" produced by neutral gas injection, the parameter $\eta_i = (d \ln T_i/dr)/(d \ln n/dr)$ can reach values, near the center of the plasma column, that are above the threshold for excitation of "macroscopic" ($\lambda_\perp > \rho_i$) ion mixing modes [2]. Thus, a substantial anomalous ion thermal conductivity can be produced.

The analysis we have performed starts from the observation that in high density regimes the ion temperature profile is close to that of the electron temperature. This is determined by the nearly Gaussian profile of the current density and is, in fact, considered to be the result of macroscopic equilibrium and stability constraints ("principle of profile consistency"), and to determine the form of the effective electron thermal conductivity [3]. Therefore when a peaked density profile is produced by pellet injection - the value of η_i is decreased and the ion conductivity anomaly can be significantly reduced in most of the plasma column.

At the same time impurity driven modes can attract impurity ions toward the center of the plasma column [4], as long as η_i remains depressed, and redistribute them toward the outer edge of the plasma column, when η_i raises as a result of the relaxation of the main particle density profile that follows a pellet injection.

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RESONANCE LOCALIZATION AND POLOIDAL ELECTRIC FIELD DUE TO CYCLOTRON WAVE HEATING IN TOKAMAK PLASMAS*

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The tokamak plasma density has been observed to drop during ECRH, and to increase during ICRF and LH. A mechanism is proposed here to explain these density variations. The perpendicular heating in cyclotron waves tends to pile up the resonant particles toward the low magnetic field side with their banana tips localized to the resonant surface. As a result, a poloidally varying electrostatic potential is expected to rise and to saturate at a level as to balance the trapping effect due to the magnetic well and the rf heating. The electrostatic potential should have strength enough to expel particles out of the magnetic well, which means $e\phi/T$ could be on the order of the well depth r/R. Consequently, an E×B drift of order $v^2/R\Omega$ comparable to the ∇B drift could result. Depending on the sign of the resonant charge, this may increase or decrease the neoclassical ion transport rate. Assuming that electrons move across the magnetic field lines more freely due to the magnetic stochasticity or other turbulent diffusions, and the particle confinement is primarily determined by the ion neoclassical transport rate, the ECRH can enhance the ion vertical drift and cause the density to drop, while the ICRF can reduce the ion vertical drift and improve the density confinement.

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SECOND HARMONIC ELECTRON CYCLOTRON HEATING*

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When electron particle orbits are trapped very near the second harmonic cyclotron resonance, quasilinear heating theory breaks down and nonlinear effects become important for particles with small $v_{\parallel}/v$. Numerical studies as well as a multiple time scale analysis demonstrate that when the change in the gyrofrequency due to the relativistic mass shift, $(\gamma - 1)\Omega_0$, is on the order of $\Omega_0|\underline{E}|/|\underline{B}_0|$, where $|\underline{E}|$ is the rf electric field strength of a perpendicularly propagating wave and $|\underline{B}_0|$ is the strength of the static magnetic field, nonlinear energy growth begins to saturate. This effect is important even for low energy electrons (~ 20 eV), resulting in periodic motion with energy excursions on the order of 5 to 10 times εmc^2 where $\varepsilon \equiv e|\underline{E}|/mc\omega = \Omega_0|\underline{E}|/\omega|\underline{B}_0|$. In EBT, such excursions are on the order of 100-200 eV on time scales several thousand times the gyroperiod. Small angle Coulomb collisions and other phase randomizing processes can cause net heating from this otherwise periodic nonlinear behavior. A Monte Carlo code has been used to determine the dependence of heating on collisionality and the possible effects on the electron distribution function. For highly collisional regimes collisions annihilate the energy excursion behavior, while in very collisionless regimes the randomizing process and the net heating efficiency are reduced. Analytic formulae are derived which describe the large energy excursions and their repetition time scale in a mildly relativistic limit. Utilizing these characteristics of the nonlinear energy excursions, estimates of the net heating rate as a function of collisionality are made and compared with the Monte Carlo numerical results.

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The Cold Plasma Model and Lower Hybrid Heating

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ABSTRACT

We study wave propagation, especially at lower hybrid frequencies, based on the cold plasma model. We show first that for the cold plasma conductivity model in Maxwell's equations, the system of equations changes type from elliptic to hyperbolic at the plasma frequency of the medium, the upper and lower hybrid frequencies, and at the electron and ion cyclotron frequencies. This provides a characterization of the resonances independent of plane stratified theory or infinite homogeneous plasma theory. For the case of an axisymmetric plasma equilibrium, the wave propagation problem, in terms of the appropriate potentials, may be represented as a fourth order system. The lower hybrid resonance surface is again a surface across which equations change type. Within the cold plasma model, plasma heating occurs only when the solutions are singular. Except near those points at which the resonance surfaces are tangent to flux surfaces, we show that the system of equations is essentially of the Tricomi type for which the solutions are well-behaved and no singularities--or wave heating--occurs. Near the points of tangency plasma heating is possible and we describe the nature of the energy flux sink. If the resonance surfaces are approximately the same as flux surfaces, as in a low beta, high field Tokamak, then heating occurs in the full surface. Aside from questions of heating, we show how to construct a physically reasonable geometric optics model in which spatial gradients or equilibrium quantities give order one corrections to ray paths and propagation characteristics.

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THE CALCULATION OF FAST WAVE FIELDS IN TOKAMAK GEOMETRY

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In this paper we describe the development of new techniques that for the first time makes feasible the calculation of the full fast wave solutions including damping and mode-conversion for realistic tokamak geometries. A key problem in the analysis of ICRF heating in tokamak is the determination of the driven wave fields in the presence of strong gradients and damping inherent to the geometric configuration and plasma conditions in these devices. The calculation of these fields is numerically difficult due to the strongly two-dimensional nature of wave propagation and the large number of wave lengths contained within the device. In addition because of the mode-conversion process, a method for handling the evanescent solutions must be developed. In this paper we will describe a method based on fourier transform techniques which allows the solution of these problems. This technique involves minimal storage and provides the potential for high spatial resolution. A number of scaling studies will be presented. Some initial conclusions are that the damping lengths are short for realistic plasma parameters. In most cases strong radial focusing occurs with standing waves directly in front of the launcher. Results indicate that in the case of strong damping, ray tracing techniques could be used to determine the fields, however, full wave methods are necessary for most cases of interest.

NONLINEAR STABILITY CONDITIONS FOR A RELATIVISTIC MULTIFLUID PLASMA*

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In preparation for establishing nonlinear stability conditions, the Hamiltonian structure is given for ideal, relativistic, multifluid plasma dynamics in the laboratory frame with the Hamiltonian functional equaling the relativistic energy minus the mass energy. The noncanonical Poisson bracket for this system turns out to be the same as for the nonrelativistic multifluid plasma, but with dynamical variables replaced by their relativistic counterparts. New constants of the motion are then derived from the Hamiltonian structure and used as Liapunov functionals for proving sufficient conditions for nonlinear stability of relativistic multifluid plasma equilibria. The nonrelativistic limit of the formulation is uniformly regular, and nonlinear Liapunov stability conditions derived earlier for a nonrelativistic multifluid plasma re-emerge in that limit.

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MONTE CARLO SIMULATION OF LOWER HYBRID WAVE SCATTERING IN THE ALCATOR C TOKAMAK*

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Recently, measurements have been made of the power spectrum of lower hybrid waves[1] in the Alcator C tokamak, using a CO_2 laser scattering technique. A detailed comparison of these experimental results with current theories for lower hybrid wave scattering from density fluctuations in tokamak plasmas[2,3] has been made. The wave propagation has been studied using a toroidal ray tracing code and a Monte Carlo technique[2] to model the scattering from the experimentally measured density fluctuations.[4] Wave absorption due to linear electron and ion Landau damping and collisional damping is calculated. The power spectra inside the plasma are simulated by launching a Brambilla power spectrum at the plasma edge, with each component weighted to a power appropriate to the waveguide phasing under consideration. The lower hybrid wave power detected by the laser is then simulated by accumulating all rays whose perpendicular wavenumbers $k_\perp$ are within the experimental resolution of the particular $k_\perp$ under consideration and whose $\underline{k}$ vectors are oriented nearly perpendicular to the laser beam at the appropriate chord location and toroidal angle (of the laser). The inclusion of density fluctuation scattering is essential in order that the wave be able to couple to the laser beam. The scattering tends to make $\underline{k}_\perp$ isotropic, thus enhancing the probability of the wavevector $\underline{k}$ being nearly perpendicular to the beam. Results will be shown for the simulated power spectra and a comparison will be made of the simulated and experimentally deduced values of parallel refractive index.

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ABSTRACT

STATIONARY FLUID MODEL OF DIVERTOR FLOWS FROM THE SCRAPEOFF LAYER

by

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A numerical stationary fluid flow model for plasma flow to neutralizer plated from the scrapeoff layer has been developed and solutions have been obtained for ranges of scrapeoff density and temperature of experimental interest. The model incorporates effects from neutral emission from the plate, pumping removal and ionization of these neutrals, crossfield transport of plasma and energy, electron and ion thermal induction and cross-relaxation, and ion viscosity. Stationary solutions are only found below a maximum scrapeoff temperature of a few eV, which temperature is a weak function of density. The divertor throat flow velocity has a maximum of a few percent of the sound speed in the middle of the range of allowed temperatures. It appears that the qualitative behavior of scrapeoff and divertor plasmas could be influenced significantly by (1) a tendency of the scrapeoff temperature to seek the value at which the throat velocity maximum occurs, or (2) a transition from the allowed stationary flow to non-stationary behavior when the main plasma temperature is forced upward and the scrapeoff temperature can no longer remain in the region where stationary solutions exist.

ABSTRACT

DYNAMIC SOLUTIONS OF THE FLUID EQUATIONS

FOR DIVERTOR AND SCRAPEOFF SOLUTIONS

by

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A time-dependent fluid flow model for the flow of plasma from the scrapeoff layer to a neutralizer plate has been developed and solutions exhibiting relaxation oscillations have been found. Among the physical effects included in the model are wall emission, pumping removal, and ionization of neutrals and are the same as those included in the accompanying paper on a stationary flow model. The mechanism of the relaxation oscillations will be discussed.

Absorption, Reflection, and Mode Coupling at the Second Cyclotron Resonance in a Weakly Relativistic, Inhomogeneous Plasma

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ABSTRACT

The relativistic linearized Vlasov equation is rescaled and solved in the boundary layer at the second electron cycloton harmonic where it is known that the geometrical optics approach breaks down for a perpendicularly stratified plasma with zero (or small) parallel refractive index. The full wave equations valid in the boundary layer is then obtained by calculating the currents and substituting into the Maxwell equations, which yields a fourth order differential equation for E_-. This equation is numerically integrated from the high field side to the low field side across the boundary layer. The asymptotic form of this equation, which corresponds to the nonrelativistic case, is solved by quadratures, and expressed analytically in the high and low field sides. These solutions are numerically matched to the solutions of the weakly relativistic full wave equation. The latter, which correspond to the incoming and outgoing extraordinary waves and quasi-electrostatic waves, are recombined to give the solutions of three physical problems, namely X-mode incidence from either side and Q-mode incidence from the low field side. In the outer region, treated by the standard geometrical optics, the appropriate Poynting theorem is derived, which enables one to calculate the fractional energy associated with the wave and the particles in a given mode. We have calculated the transmission, reflection, mode conversion, and absorption for the three problems mentioned above. The nonrelativistic case, which is expressed analytically, shows that the incident energy which is not transmitted is mode converted (or partially reflected in the low field side incidence), thus yielding zero absorption. The weakly relativistic treatment yields the fractional absorbed energy due to the broadening. The results are presented in terms of two parameters, namely $X = (\omega_p/\omega)^2$, and $\eta^2\tilde{L}$, where $\eta = v_e/c$ is the smallness parameter, and $\tilde{L}$ is the characteristic scale length for the external field normalized to the free space wavelength. It is found that in general the absorption in the low field side incidence is higher due to the smaller mode conversion rate.

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Electron Transports and Microscopic MHD Turbulence

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ABSTRACT

Anomalous electron transports in low beta collisionless plasmas occur only in the presence of turbulent electric fields in the direction parallel to the magnetic field.[1,2,3]

The origin of such parallel electric fields in MHD frequency range is the finite ion gyroradius and/or electron inertia effects. Therefore MHD turbulence which is responsible for electron transport should have an anisotropic spectrum with $k_\perp \rho_i$, $k_\perp \rho_s$ or $k_\perp c/\omega_{p\ell} \simeq 0(1)$ with parallel wave numbers in the MHD scale. Fluctuations with this type of anisotropic spectrum lead to turbulence even at very low levels such as $\tilde{n}/n_o \simeq \rho_s/L_n$ or $\tilde{B}/B_o \simeq \rho_s/R$ (R is the radius of curvature).

MHD equations appropriately modified to describe this type of turbulence[4] are presented with emphasis on the role of turbulence on electron transports.

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A THEORETICAL MODEL FOR INTERPRETING CONFINEMENT IN FIELD-REVERSED CONFIGURATION EXPERIMENTS

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A model, QUASI, was devised to simulate decay of particles and flux in a FRC. QUASI uses a self-similar approach, which is equivalent to assuming quasi-steady radial profiles of the density and magnetic field: i.e. $n/n_m = \beta(u)$, and $B/B_e = b(u)$, where $u \equiv (r/R)^2-1$. The model allows time-dependent n_m (maximum density), B_e (external magnetic field), and R (radius of magnetic axis), but, assumes constant profile functions, $\beta(u)$ and b(u). Although QUASI is 1D, it accounts for 2D effects as follows: 1) pressure is uniform on closed flux surfaces, and 2) the "average-β condition", $\beta = 1-(R/r_c)^2$, is applied (r_c is the coil radius). Quasi-steady conditions are assumed, i.e. $\beta=1-b^2$, and the temperatures T_e, T_i, are taken to be spatially uniform.

By applying QUASI to a wide range of conditions, approximate analytic expressions have been determined from which the resistivity (magnitude and approximate profile) can be inferred if the confinement times, measurable parameters are known. These expressions have been used to interpret the transport behavior in TRX-1. Several major conclusions have grown out of this study, which are summarized in the following.

The resistivity averaged only 3 to 4 times classical (based on an electron temperature of 100 eV) when TRX-1 was operated in the programmed-formation mode with good preionization characteristics. The inferred resistivity profiles are quite flat: $\eta(R)$ is typically 70-80 percent of its value at the separatrix, and exceeds 1/3 for all the available data. In a nonnegligible number of shots (about 15 percent of the data base), η was actually higher at R than at the separatrix.

The observed confinement of particles was compared to the predictions from lower-hybrid-drift theory and found to exhibit major differences. 1) The strong peaking of η near the separatrix, which is characteristic of the LHD, was not observed. 2) The resistive anomaly near the magnetic axis cannot be explained by local LHD theory. 3) The dependence of particle confinement on the temperature and the plasma length differed significantly from LHD predictions.

HAMILTONIAN REPRESENTATION OF HELICAL FORCE-FREE MAGNETIC FIELDS*

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Abstract

Because of the possible significance of helical states for the dynamic sustainment of the reversed-field pinch configuration, we have started to explore their properties. We shall demonstrate that when a helical magnetic field satisfying $\vec{\nabla}\times\vec{B}(r,\phi)=\lambda\vec{B}(r,\phi)$, (where ϕ is the helical coordinate $m\theta+kz$) is decomposed into components parallel and perpendicular to the Beltrami vector $\vec{h}=(kr\hat{\theta}-m\hat{z})/(k^2r^2+m^2)$ that points in the direction of constant ϕ, then

$$\vec{B}(r,\phi) = -\lambda H(r,\phi)\vec{h} - \vec{\nabla}H(r,\phi) \times \vec{h}$$

This elegant formula becomes even more resplendent when one realizes that the function H is merely the generating function for the magnetic field lines through Hamilton's equations:

$$\frac{dr}{dz} = \frac{\partial H(r,\phi(r,p))}{\partial p} \quad , \quad \frac{dp}{dz} = -\frac{\partial H(r,\phi(r,p))}{\partial r} \quad .$$

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TRANSPORT DESCRIPTION OF THE RISETIME OF SAWTOOTH OSCILLATIONS IN REVERSED-FIELD PINCHES*

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High Θ operation ($\Theta \equiv B_{\vartheta wall}/\langle B_{\varphi}\rangle \geqslant 1.55$) of the Los Alamos ZT-40M Reversed-Field Pinch (RFP) device is characterized by discrete sawtooth events.

The falling part of the sawtooth has been linked to m = 1 tearing modes and is coincident with observable increases in the toroidal magnetic flux.[1] This behavior may account for the anomalous toroidal magnetic flux generation "dynamo" observed in the RFP.

The current work utilizes a one-dimensional transport description to model the time between tearing events (i.e., the risetime of the sawtooth). Using experimentally measured boundary conditions for the toroidal voltage and magnetic field at the wall, the temporal waveform of the toroidal magnetic flux, Θ, and the toroidal plasma current can be reproduced provided the resistivity profile has significant gradients. This result suggests that dynamo action may be restricted to the tearing events.

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Abstract submitted to 1984 Annual Controlled Fusion Theory Conference, Incline Village, Nevada, April 11 - 13, 1984.

SELF-CONSISTENT HAMILTONIAN AND DISSIPATIVE FORMULATIONS OF NONLINEAR PROCESSES*, Allan N. Kaufman, Philippe L. Similon, and Bruce M. Boghosian, Physics Department, Lawrence Berkeley Laboratory, and Lawrence Livermore National Laboratory, University of California, U.S.A.

Theories of nonlinear plasma dynamics utilize the concept of averaging, to reduce the mathematical description from a detailed high-frequency treatment to an approximate, but more useful, low-frequency treatment. Examples are the guiding-center plasma and gyrokinetics [1], the waves plus oscillation-centers system [2], and the several dissipative kinetic equations. A major issue in such reductions is the demand for self-consistency, and the preservation of valid conservation laws.

Hamiltonian methods [3] guarantee self-consistency and yield conservation laws of Noether symmetries. They also yield concise formulations, make relationships manifest, and allow for powerful stability analyses [4]. A systematic approach to deriving these Poisson structures will be presented. Starting from an action principle for the family of phase-space trajectories and electromagnetic fields, equivalent to the Vlasov-Maxwell system, a Lie transform is performed on the phase-space coordinates. The choice of the Lie generating function w determines the nature of the reduction. One choice, with w time-independent but gyrophase-dependent, yields the self-consistent gyrokinetic system, with Poisson brackets on the set of reduced observables. Another choice, with w linear in the time-dependent fields, yields the Poisson structure for wave propagation, ponderomotive effects, wave-particle resonance, wave scattering, and three-wave interaction.

To deal with dissipative systems, a novel type of bracket structure [5] is introduced, approporiate to the conservation of energy and momentum and the monotonic increase of entropy. A set of rules is established to determine this structure in particular cases. Each observable evolves via a Poisson Bracket on a Hamiltonian and a Dissipative Bracket on the entropy. The latter bracket guarantees Onsager symmetry. This formalism is applied to a broad class of dissipative Hamiltonian systems: the kinetic equations governing particle collisions, wave-particle resonance (linear and nonlinear), and three-wave resonance; and the various fluid models, such as Navier-Stokes and resistive MHD. Implications for stability criteria are under study.

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* Work supported by the U. S. Department of Energy

COMPARISON OF 3-D MOMENTS AND FINITE DIFFERENCE INVERSE MHD EQUILIBRIUM CODES*

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To facilitate the development of three-dimensional plasma transport simulations, we have undertaken a comparative evaluation of the Bauer-Betancourt-Garabedian equilibrium code, which solves $\underset{\sim}{J} \times \underset{\sim}{B} - \nabla P = 0$ for nested magnetic surfaces using finite differences, and the 3D moments code (MOMS3D), which uses a Fourier expansion technique. The version of the Bauer-Betancourt-Garabedian code we have used is that described in Ref. 1. The method underlying the algorithms in the moments code is given in Ref. 2. Several fixed-boundary configurations, including heliotron, ATF, and heliac, have been analyzed to assess the following equilibrium properties: 1) convergence rates (with mesh size) of the magnetic axis and general magnetic surface shapes, 2) magnetic well depth $dV/d\Phi$ (measuring interchange stability), 3) inductance and other geometric surface-averaged coefficients relevant to transport processes, and 4) approximate cpu time required to achieve a given level of force residual. Discussions with O. Betancourt on the choice of parameters, and his recommendations for optimization are gratefully acknowledged.

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Beam-Driven Drift Instability in a Thermal Barrier Cell

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ABSTRACT

A low frequency instability ($\omega \ll \Omega_{ci}$) is sometimes seen in the **TMX-U** device at **LLNL** when the neutral beams are turned on in the thermal barrier cells. One possible explanantion is that a drift wave couples with beam modes from the injected ions in an unstable fashion. Our previous work for this instability (Bull. Am. Phys. **28** , Num. 8, 7Q6 (1983).) has been limited to the local approximation for both linear theory and particle simulations. We have now extended both the linear theory and the particle simulations to include a more complete treatment where the local approximation is *not* made. A comparison is given in the results obtained from the local approximation and the results obtained from using a nonlocal model. Even when the nonlocal and local growth rates are very close the instability may saturate in different fashions. Work supported in part by DOE and in part by ONR.

A NONLOCAL TREATMENT OF DRIFT WAVES IN CYLINDRICAL GEOMETRY

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We present here the results of a study of drift wave instabilities in cylindrical geometry. The magnetic field $\underline{B}=B(z)\hat{\underline{z}}$ is assumed uniform. The equilibrium distribution function is uniform in z, and has a Gaussian dependence on both energy and angular momentum $P_\phi=mr^2\dot{\phi}+qrA_\phi/c$, resulting in a density profile which is Gaussian in r. A general code has been implemented on the NMFECC to solve this problem. For each azimuthal mode number, the integral equation in k space for the electrostatic potential ϕ is converted to a matrix eigenvalue problem by expanding $\phi(k)$ in Laguerre functions of k, with ω as eigenvalue. Truncation of the expansion yields a dispersion relation in the form of the vanishing of an NxN determinant. The NxN matrix equation is solved numerically and the eigenmodes $\phi(r)$ in configuration space are computed. Localization of the drift modes takes place at the periphery of the plasma where the vacuum terms are important. The lowest radial eigenmode is not, in general, the fastest growing mode. Comparison with WKB slab theory[1] shows general agreement for the m dependence of the frequency and growth rate versus azimuthal mode number.

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THEORY OF R.F. STABILIZATION OF AXISYMMETRIC TANDEM MIRRORS*,

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Recent experiments [1] on r.f. stabilization of flute instability in axisymmetric mirrors has stimulated much theoretical research to describe the nonlinear interaction of the high frequency fields with the low frequency modes of the plasma. Two main issues are 1) the dependence of the stabilization on the difference between the frequency of the r.f. field and the ion gyrofrequency, and 2) the threshold intensity of the r.f. field necessary to achieve stabilization. In contrast to most other theories, the present approach emphasizes the self-consistent treatment of the r.f. field and the plasma during the instability, which is essential close to the gyrofrequency. The action principle, for the Lagrangian displacements of the plasma and for the electromagnetic fields (with the antenna), is averaged over the fast time scale. A Hamiltonian and noncanonical Poisson bracket for the fields are derived, and provide an Eulerian description of the system. The evolution equations for the oscillation-center densities and averaged electromagnetic fields involve ponderomotive forces and magnetization currents created by the r.f. fields. The relation between the ponderomotive potential and the inductive load of the antenna is obtained. Besides the linear stability analysis of this system of equations, the Hamiltonian formalism allows the use of techniques that establish sufficient conditions for nonlinear stability [2]. The Hamiltonian, combined with Casimir functionals (i.e. whose Poisson bracket with any functional vanishes), serves as a Lyapunov functional: its local but strict extrema in functional space are nonlinearly stable equilibria. Specific stability criteria are obtained for axisymmetric plasma equilibria in the r.f. fields. Plasma simulations are under preparation for comparison with the theory.

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EFFECTS OF TRAPPED HOT IONS ON HIGH-BETA MHD MODES*

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The effects of anisotropic hot ions resulting from auxiliary heating are considered in connection with global ideal and resistive MHD modes for high-beta tokamak plasmas in a fixed and free boundary geometry. Reduced MHD equations with two equations of state[1] for isotropic and anisotropic pressure are used. As the temperature or the pressure of the trapped anisotropic component increases, the growth rate is enhanced and the oscillation frequency becomes finite. This destabilization of resistive as well as ideal modes is similar to that of ideal internal kink mode.[2] When the temperature of anisotropic component is very large, the trapped region may respond rigidly to low frequency MHD modes, leading to a stabilizing influence to the global ideal and resistive MHD modes as well as to short wavelength ideal ballooning modes.[3]

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CONVECTION IN TANDEM MIRRORS CAUSED BY TEMPERATURE INHOMOGENEITY

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The experimental results of TMX-U suggest that the radial transport may be much larger than expected. It is reminiscent of experiments with Q-machines many years ago. The radial diffusion rate of Q-machine plasma was often much larger than that of the classical rate. It was discovered that the end plate temperature distributions play a key role. The electron temperature and therefore the sheath potential are dependent on the local temperature of the end plates. As a result, the electrostatic potential distribution of the plasma reflects the temperature distribution of the end plates. The plasma undergoes the convective motion due to the electrostatic potential. Various mechanisms which produce an azimuthal electric field in the tandem mirrors have been considered.[1]

We investigate the electrostatic convection in the central cell of a tandem mirror device driven by either nonuniformity of the electrostatic potential of the end cells or the nonuniformity of temperature in the central cell. We use a simple model where the end-cell is a double sheath of the electrostatic potential. The potential of a flux line ϕ_e in the central cell is determined by equating the ion and the electron losses along the flux line. The electron temperature inhomogeneity ΔT_e results in the potential inhomogeneity of $\Delta\phi_e/\phi_e = (\Delta T_e/T_e)(1 + T_e/T_i)^{-1}$. The potential inhomogeneity results in corrective diffusion and the rate is given by $D = (k_\perp^2)/B^2 \int \langle\Delta\phi_e(t)\,\Delta\phi_e(t + \tau)\rangle\, dt$. The correlation time may be determined either by diffusion itself or by the spread in ∇B drift velocity. For a given temperature inhomogeneity, one can find the wavenumbers where the diffusion time is shorter than the correlation time given by the spread in the drift velocity. The diffusion rate is given by $D = (T_e/eB)[1/(1+T_e/T_i)](\Delta T_e/T_e)$. It scales like the Bohm rate. Since the projected confinement time of MFTF-B corresponds to 10^4 times Bohm time, extreme care is needed to keep the electron temperature and the end cell potential uniform.

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STUDY OF GENERALIZED TORODIAL CUSP CONFIGURATIONS†

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ABSTRACT. Hot electrons as well as hot ions are a desirable feature of any fusion device. We investigate by particle simulations (in slab geometry) and simple theory two variants of the Toroidal Cusp Experiment[1] (TCX) with an eye to achieving hot electrons, while retaining its large direct ion heating feature. A torodial field added to the TCX configuration, with cusp magnets arranged poloidally to partly cancel cusp trapping of the electrons insures flow across the cups and electron heating. Helical winding of the cusp magnets around the torus with pitch $\theta \gg (m/M)^{1/2}$ allows trapped electron flow on average helical paths; however, ions can still flow across the cusps and the $\underset{\sim}{J} \cdot \underset{\sim}{E}$ heating of ions and electrons can be varied at will.

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† Work supported by WSDOE

RELAXATION OF TOKAMAK DISCHARGES

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Recently, a quasi-thermodynamic model has been developed for relaxation of tokamak discharges dominated by tearing modes of single helicity[1]. In this model, the potential energy of the plasma is minimised subject to a set of global invariants preserved exactly by ideal, and approximately by a class of resistive modes. We present linear and nonlinear estimates of the decay rates of these "invariants". We show that in the final relaxed state, the spatial gradient of the parallel current and the plasma pressure vanishes identically at the rational surface corresponding to the dominant mode, and present numerical solutions which demonstrate this property. These finite-beta equilibria are <u>not</u> force-free (unlike Taylor's[2]), and may be interpreted as states to which tokamak plasmas relax on the timescale of resistive instabilities. We present detailed studies of the ideal and resistive stability of these minimum-energy equilibria.

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DESTABILIZATION OF MICRO-TEARING MODES BY CROSS-FIELD TRANSPORT*

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We have found that the semicollisional tearing mode is driven unstable in the presence of an electron temperature gradient and classical perpendicular transport, even for $\Delta' < 0$. The dispersion relation can be found analytically in the long mean-free path limit. For RFPs and spheromaks, i.e., for $qR/a \sim 1$, the growth rate is a substantial fraction of ω_{*t}, the diamagnetic drift frequency based on the temperature gradient, and Δ' is important only for very short wavelength modes, with $\Delta' \sim -k$, where it can stabilize the mode. For tokamaks with classical electron transport, i.e., for $qR/a \gg 1$, the destabilizing effect of cross-field transport is extremely small and does not affect the stability of the mode. However, the instability can have a substantial growth rate in a tokamak with anomalous electron transport $\eta_\perp/\eta_{\perp c\ell} \sim (R/a)^2$. We have numerically studied the effects of thermal force, curvature, and thermoelectric effect on this instability, and find that the first two effects further destabilize the mode, while the last can decrease growth rates but not stabilize.

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A Perturbation Solution of the Fokker-Planck Equation for High Energy Ion Transport

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A useful description of fast heavy ions suffering small angle deflections and weak energy coupling during collisions in one dimension is given by the Fokker-Planck equations

$$\left[\frac{\partial}{\partial t} + \mu v \frac{\partial}{\partial x}\right] f(x,\mu,v,t) = \alpha \, [\frac{\partial}{\partial v} U(v) \, f(x,\mu,v,t) + \tag{1}$$

$$+ vT(v) \frac{\partial}{\partial \mu} (1-\mu^2) \frac{\partial}{\partial \mu} f(x,\mu,v,t)] + v^2 S(x,\mu,v) \, \delta(t)$$

where U and T are prescribed functions. Even for relatively uncomplicated transport situations, no known analytical solutions exist for this Fokker-Planck equation, and Eq. (1) must be numerically evaluated. It is the purpose of this presentation to generate a highly accurate numerical solution of Eq.(1) when the collision term can be considered a perturbation on the particle trajectory (when $\alpha t \ll 1$). First consider a source emitting ions uniformly, in velocity and isotropically in direction at $x = 0$

$$S(x,\mu,v) = \frac{\delta(x)}{4\pi v^2}$$

in an infinite homogeneous medium. Then by expanding the intensity f in an infinite series of collided densities, it can be shown that f has the following representation as a distribution:

$$f(x,\mu,v,t) = \sum_{n=0}^{\infty} (\alpha t)^n \sum_{k=0}^{2n} t^k A^n{}_k(\mu,v) \, \delta^{(k)}(x-\mu vt) \tag{2}$$

where

$$A^n{}_k = \frac{1}{n+k} \quad vT \frac{\partial}{\partial \mu} (1-\mu^2) \frac{\partial A^{n-1}{}_k}{\partial \mu} + \frac{\partial U}{\partial v} A^{n-1}{}_k + U \frac{\partial A^{n-1}{}_k}{\partial v} -$$

$$-\left[v^2 T(1-\mu^2) \frac{\partial A^{n-1}{}_{k-1}}{\partial \mu} + v^2 T \frac{\partial}{\partial \mu} ((1-\mu^2) A^{n-1}{}_{k-1}) + \mu \, U A^{n-1}{}_{k-1}\right] \tag{3}$$

$$+ v^3 T(1-\mu^2) A^{n-1}{}_{k-2} \;, \; A^0{}_k = \delta_{k,0}$$

and

$$A^n{}_k \equiv 0 \;, \; k<0, \; k>n \;.$$

Thus, the solution to the initial value problem

$$\psi(x,\mu,v,0) = \frac{g(x)}{4\pi v^2}$$

where g(x) is a sufficiently smooth function, is obtained by convolution of the initial distribution with Eq. (2) yielding

$$\psi(x,\mu,v,t) = \sum_{n=0}^{\infty} (\alpha t)^n \sum_{k=0}^{2n} t^k A^n{}_k(\mu,v) \, g^{(k)}(x-\mu vt) \quad . \tag{4}$$

In general, this representation of ψ is an asymptotic series allowing numerical evaluation when $\alpha t \ll 1$. The coefficients $A^n{}_k$ can be numerically evaluated by several methods including, polynomial expansion, continued differentiation or symbolic manipulation. In this way, highly accurate short time numerical solutions can be generated and compared to numerical results obtained via other algorithms proposed for more general situations.

MORE ABOUT THE SPECTRUM OF THE RESISTIVE ALFVÉN WAVE*

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It is found that the upper spectral line of the Alfvén wave coming from the largest accumulation point is degenerate for a Reversed-Field Pinch Configuration. A new spectral line is discovered very near to the one reported before.[1] The modes in this new spectral line are found to have the same mode structures as the ones in the old spectral line, except the parity difference.

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MICROWAVE INDUCED NEOCLASSICAL TRANSPORT IN EBT GEOMETRY*

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ABSTRACT

Microwave scattering in pitch angle is included in a simplified drift kinetic equation for electrons assuming (1) a Lorentz collision operator, (2) large ambipolar electric fields, $\Omega_E \gg \Omega_{\nabla B}$, and (3) moderate to high collisionality $\nu_{RF}/\Omega_E \geq (r/R_T)^{3/2}$. This equation is solved numerically with energy as a parameter to estimate the effect of microwave scattering on neoclassical transport. Strong absorption of the microwaves near the Doppler shifted resonance leads to relatively rapid pitch angle scattering for high energy ($mv^2/2 \geq kT_e$) particles with large $v_\parallel$ ($v_\parallel/v \geq 0.5$). For example, if the microwave electric field far from resonance is 40 V/cm, then the neoclassical diffusion rate for 600 eV electrons with density 6×10^{11} cm^{-3} is enhanced by about a factor of 5, and $\nu_{RF}/\Omega_E \sim 1$ for $v_\parallel/v \geq 0.5$.

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CONFINEMENT AND TRANSPORT IN STELLARATORS

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We are incorporating a model of particle transport in the three-dimensional equilibrium and stability code BETA, which is about to be released for general usage [1]. We introduce Boozer's coordinates ϕ, ψ and s defined by the Clebsch representations

$$B = \nabla s \times \nabla\psi = \nabla\phi + \zeta \nabla s$$

of the magnetic field. From his theory we derive the partial differential equation

$$\frac{\partial\lambda_{\parallel}}{\partial\phi} = \frac{\partial\rho_{\parallel}}{\partial\psi}$$

relating a guiding center step size $\lambda_{\parallel}/|\nabla s|$ to the parallel gyroradius $\rho_{\parallel}$. In terms of the Fourier coefficients a_{mn} of $\rho_{\parallel}$, we find for $\lambda_{\parallel}$ the resonant expression

$$\lambda_{\parallel} = \Sigma \frac{m\, a_{mn}}{n - \iota m} e^{im(\psi-\iota\phi)+in\phi} ,$$

where ι stands for the rotational transform. A transport coefficient for circulating and trapped particles of the form

$$D = \nu \int \frac{\lambda_{\parallel}^2}{(\nabla s)^2} d\phi\, d\psi\, dF + \frac{\nu_B^2}{\nu} \int \frac{(\lambda_{\parallel}-\lambda_0)^2}{(\nabla s)^2} d\phi\, d\psi\, dF$$

has been calculated, where F is an appropriate probability distribution, ν is the collision frequency, ν_B is an approximate bounce frequency, and λ_0 is a constant of integration that can be determined optimally over each banana orbit. Good correlation has been established between the minimum of D with respect to ν and plateau values of the transport coefficient obtained from Monte Carlo calculations by H. Wobig for the Wendelstein W VII-AS experiment, for a typical Heliac, and for a reference $\ell = 2$ stellarator.

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Magnetic Equilibrium and Single Particle Orbits in EBS*

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The Elmo Bumpy Square (EBS) consists of four bumpy cylinders connected by four high field "corners." Here we compare the magnetic equilibrium properties of an EBS with those of EBT-I/S. We also give a qualitative discussion of single particle drift orbits which provides further insight into the detailed numerical calculations.[1]

The standard theory of closed line (and mirror) equilibria is sketched using both MHD and drift kinetic formalism. The drift kinetic approach provides a more direct connection to the fact that pressure surfaces for isotropic distribution functions are "average drift surfaces" (surfaces of constant $\oint d\ell/B$). An analytic calculation of the pressure surfaces shows that they are circular in cross-section (and constant along field lines)—in agreement with numerical results. As in the EBT-I/S case these circles are shifted inward by toroidal effects. Unlike EBT-I/S, the toroidal effects for EBS are concentrated in the high B corners and the shift shows an additional dependence on B_{corner} (or global mirror ratio). It is this dependence on global mirror ratio which is exploited to reduce the pressure surface shift (average drift surface) as well as the shift of passing and transitional particles.

The drift behavior of trapped, passing and transitional particles is usually obtained using bounce averaged equations. Here we justify this procedure and discuss the motion on the shorter (local drift) time scale—either one of which may be used to gain qualitative insights into the behavior of single particles—and hence insights into collective effects such as transport and heating.

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

+Computer Sciences Division

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RENORMALIZED TOROIDAL MHD EQUILIBRIA*

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The magnetohydrodynamic equilibrium problem in a toroidal-helical configuration is reformulated by a renormalization of unperturbed cylindrically symmetric equilibrium state by using the average of the helical perturbation. Although the averaged helical quantities are cylindrically symmetric, they do not satisfy, in general, the Maxwell equations. It makes an essential difference in the process of the reformulation of the equilibrium problem by using the renormalized quantities. By this renormalization, one will see that the method employed by Shafranov which originally was applicable only to the system where the axial plasma current determines the magnetohydrodynamic equilibrium, can be applicable to more general cases with arbitrary plasma current in the presence of helical field including stellarator and OHTE. To the first order in toroidal effect, a general differential equation for the toroidal displacement is derived, which reduces to the tokamak result in the weak helical field limit and to the stellarator result in the weak plasma current limit.

*Work supported by U.S. DOE Contract DE-AT03-84ER53158.

MONTE CARLO ESTIMATES OF TRANSPORT RATES IN EBT WITH ASYMMETRIC POTENTIAL PROFILES*

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ABSTRACT

The ORNL Bounce-Averaged EBT Monte Carlo Transport code has been used to study loss rates in EBT for three cases. (1) Closed electrostatic potential contours which coincide with the α-contours, (2) in-out asymmetric potential profiles producing crescent-shaped equipotential surfaces, and (3) asymmetric potential profiles with open equipotential contours (i.e., potential contours that intersect the "wall"). Since low energy particles are strongly influenced by the $E \times B$ drift to roughly follow the potential contours, such asymmetric potential profiles can be a significant loss mechanism for such particles. This idea has been quantified with the Monte Carlo calculations to be presented. We will show results for the particle and energy confinement times for the three cases mentioned above.

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+Computer Sciences at Oak Ridge National Laboratory.

LIMITER STABILIZATION OF EXTERNAL KINK MODES*

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Based on a cylindrical model, a ring limiter may have an important stabilization effect on external kink modes.[1] This question is re-examined for toroidal limiters and more realistic toroidal geometries with the GATO code[2] using proper boundary conditions. The study includes the effects of the size of the limiter, the poloidal location of the limiter and the optimization of β with respect to current profile parameters, in the presence of a limiter.

[1]J.P. Freidberg *et al.,* Phys. Rev. Lett. *51,* 2105 (1983).
[2]L.C. Bernard *et al.,* Comput. Phys. Commun. *24,* 377 (1981).
*Work supported by U.S. DOE Contract DE-AT03-84ER53158.

RF DRIFT PUMPING OF THERMAL BARRIERS*

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Drift pumping induces radial drift and energy transport of thermal-barrier ions with azimuthally varying of fields. Two rf field configurations, one with magnetic perturbation perpendicular to ($\underline{\tilde{B}}_\perp$) and another one parallel to ($\underline{\tilde{B}}_\parallel$) the unperturbed B field, have been investigated analytically. Their resonant frequencies are $\omega = k\omega_b \pm \omega_d$, $k = 0, 1,2, \cdots$, where ω_b and ω_d are the bounce and azimuthal drift frequencies. For $\underline{\tilde{B}}_\perp$, the diffusion coefficient is optimum when $\underline{\tilde{B}}_\perp$ is perpendicular to the thin fan, then scaling as $D \sim [Ky\underline{\tilde{B}}_\perp(mV_\parallel^2 + \mu B)]^2/\Delta\omega$, where Ky is the curvature normal to the thin fan and $\Delta\omega$ is the rf frequency bandwidth (provided that resonances overlap). The resulting pumping rate is marginally adequate for TMX-U with throttle coils, and adequate for MFTF-B. $\underline{\tilde{B}}_\parallel$ perturbation appears to be less effective than $\underline{\tilde{B}}_\perp$. From simulations of TMX-U without throttle coils with $\underline{\tilde{B}}_\perp$ field, we have verified stochasticity when resonances from several different drift frequencies overlap. Comparison between analytic and simulation results is presented.

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Predictions of Divertor Regions in IMS and ATF-1 *

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The edge region of any plasma confinement device is important to consider for controlling impurity diffusion into the plasma and energy transport away from the confined region. To design effective divertors for use in a device it is necessary to know where particle flux emerges from the confinement volume into an area which can be used as a neutralizing region. A large contribution to this flux results from particles free-streaming along the field from the separatrix to the coil region with small perpendicular drifts.

A numerical code has been used which follows field lines, from filamentary conductors, launched just outside the separatrix region. The field lines are followed until they reach a cutoff radius which is chosen to be the coil minor radius, or just beyond, such that ample space is provided for any actual divertor designs.

This code has been used to predict the modular divertor bundles present in the Interchangable Module Stellarator (IMS), an ℓ=3, 7 field period device which is operational at the University of Wisconsin. The results compare well to the presence of experimentally observed particle flux bundles. The code is also being used to predict the location and shape of the divertor region in ATF-1.

ATF-1 is an ℓ=2, 12 field period torsatron under construction at ORNL, scheduled to begin operation in 1986. Initial results show a helical divertor pattern which is as would be expected from an ℓ=2 torsatron.

* Supported by DOE Contract No. DE-AC02-84ER53166, NSF Grant No. ECS-8206027 and ORNL contract No. 19X-89613C.

Self Consistent and Combined Effects of the Wave Breaking, of the Trapping Effect and of the Wave Damping in a Hot Magnetoplasma

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ABSTRACT

The behavior of strong magnetosonic waves in a hot magnetoplasma is investigated for $\omega_{ci}<\omega<\omega_{lh}$ and $\theta=90°(\theta=(\vec{k},\vec{B}_o))$ by using a 1-2/2 dimensional, relativistic, fully electromagnetic, particle code with both ions and electrons; ω_{ci}, ω and ω_{lh} and respectively the ion gyrofrequency, the pump wave frequency and the lower hybrid frequency. A longitudinal electric field due to space charge effects builds up and accelerates the ions until some of them reach the phase velocity of the wave and become trapped. The amplitude of the waves is sufficiently strong that wave steepening (crest overtaking of troughs) takes place and harmonics develop. The time at which this occurs agrees well with theoretical estimates. Essentially a shock like configuration develops which is followed after some time and enhanced by ion trapping. Simultaneously, in a good agreement with the theoretical predictions, strong wave particle resonant interaction occurs during the trapping time allowing some ions to gain a net energy and to become detrapped. Strong ion heating and acceleration result in the plane perpendicular to $\vec{B}_o$ at the expense of the wave which is largely damped. The competitive effects of the wave breaking, of the trapping and of the wave damping, combined together by the self consistency of the model are discussed. Conditions under which such conditions might be induced in fusion plasmas are considered.

Transport Calculation for A Field Reversed Configuration*

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The compact torus transport code CTT has been applied to the simulation of the transport time scale evolution of a field reversed configuration plasma. The plasma is assumed to evolve through a sequence of equilibria. The calculation proceeds by alternating between the calculation of 2-D axisymmetric equilibrium and 1-D transport. The equilibrium calculation uses flux surface coordinates and finite elements. The equilibrium is determined by the adiabatic quantities entropy and poloidal flux. The equilibrium calculation proceeds by alternating between the solution of the 2-D Grad-Shafranov equation and a 1-D flux surface averaged Grad-Shafranov equation. The transport calculation consist of the simultaneous solution of three 1-D transport equation for the ion density, electron entropy and ion entropy. The physical processes which are modeled by this calculation are, classical transport, Joule heating of electrons, collisional transfer of energy between ions and electrons, radiation cooling of electrons due to impurities, loss of particles due to flow along open field lines, and anomalous transport based on lower-hybrid-drift scaling. Examples of this calculation are presented for the FRX-C experiment.

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Mercier Stability for Plasmas with Flow

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ABSTRACT

The Mercier stability criterion against modes localized about a flux surface can be obtained by minimizing the energy, even though a minimum energy principle does not exist for general modes in rotating plasmas. The energy has a minimum only in a coordinate frame rotating with the plasma toroidal frequency Ω. The instability corresponds to accumulating unstable eigenmodes at real points $\omega = m\Omega(\psi_o)$, where ψ_o is a rational surface and m is the azimuthal mode number.

A derivation simpler than the traditional one[1] is based on considering the energy of a subsystem of equations which is hyberbolic with no ψ-derivatives[2]. The same subsystem was used before[3] to investigate ballooning modes. The relation between the Mercier and ballooning criteria is investigated, as well as the effects of the flow which appear to be destabilizing.

1. J. Greene and J. Johnson, Phys. Fluids (1962), p. 510.
2. E. Hameiri, Phys. Fluids (1983), p. 230.
3. E. Hameiri and P. Laurence, J. Math. Phys. (1984).

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SHERWOOD THEORY MEETING 1984

April 11 to 13

The Importance of Electron Collisions for Ion Transport in Tokamaks*

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In calculating ion transport the collisions of ions with electrons have generally been neglected. This is a good approximation for $T_e > T_i$ but not when $T_e << T_i$. Also, the friction force experienced by ions with velocity v in the tail of the distribution (f_{io}) is proportional to v^{-2} for i-i collisions but proportional to v for i-e collisions; hence electronic collisions will be relatively more important for transport processes such as ion heat conduction where particle contributions are strongly weighted by their energy. From the classic paper of Herdan and Liley[1] the ion heat conduction $\parallel \underset{\sim}{B}$ is given by,

$$q_{\parallel} = 3.1 \; p_i \; \nabla_{\parallel} T_i / m_i \left[\nu_{ii} + \frac{15}{4} \left(\frac{m_e}{m_i} \right) \nu_e \right] \quad , \qquad (1)$$

Thus i-e collisions increase the energy-weighted friction force experienced by the ions due to $q_{\parallel}$ by the factor $[\nu_{ii} + 3.75(m_e/m_i)\nu_e]/\nu_{ii}$ and hence Pfirsch-Schluter ion heat conduction is increased by this factor. Note that $3.75 (m_e/m_i)\nu_e > \nu_{ii}$ for $T_e < T_i/4$. For banana regime heat conduction the ν_e term is somewhat less important because it has an extra factor $(r/R)^{1/2}$; the friction force due to i-e collisions involves energy scattering and is weak for trapped particles. However, for the 2-component f_{io} observed in PDX, the i-e collisions are very important for ions in the enhanced distribution tail. Using the observed PDX data the resultant ion heat conduction, allowing for the enhanced tail and i-e collisions, is an order of magnitude larger than the standard neoclassical value. Also with the same PDX data, the i-e contribution to ion viscosity ($P_{\parallel r}$) is seven times larger than the standard neoclassical value.

[1]R. Herdan and B.S. Liley, Rev. Mod. Phys. 32, 731 (1960).

*Work supported by USDOE.

Thermal Effects on the Efficiency of Doppler-Shift Dominated Cyclotron Masers:

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Due to its tuneability, high efficiency, and favorable frequency scaling with electron beam energy, a Doppler-shift dominated cyclotron maser is a viable competitor against gyrotron and free electron laser in the milli-meter and sub-milli-meter wavelength ranges. It is demonstrated by particle simulations that a relativistic electron beam with 1.25 Mev energy, 1.5 kA current and 3% momentum spread can convert 13% of its energy into electromagnetic radiation based on the Doppler-shift dominated cyclotron maser mechanism. The output power can reach 200 MW at $\omega_r \simeq \gamma\Omega_o$ where γ is the beam relativistic factor and Ω_o is the non-relativistic electron cyclotron frequency. The simulation results show that an increase in beam thermal spread reduces the available free energy $\Delta\gamma = \gamma_o - \gamma_R$ by increasing the beam resonant energy γ_R where γ_o is the initial beam energy and substantially decreases the conversion efficiency. Further increase in thermal spread eventually changes the saturation mechanism from phase trapping to energy depletion.

CYCLOTRON MASER RADIATION FROM MILDLY RELATIVISTIC ELECTRON DISTRIBUTIONS*

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The cyclotron maser instability results from the relativistic mass dependence of the cyclotron frequency, which leads to phase bunching in the electron gyration obits. The radiation is generated near the electron cyclotron frequency (or its harmonics) and propagates primarily in the fast-wave branch of the R-X mode. This instability is believed to produce the radiation observed in such diverse settings as laboratory gyrotrons, magnetic mirrors, and radio emissions from the Earth, Jupiter, and the sun. Recently, Lau and Chu[1] performed a linear stability analysis for the case of emission parallel to the magnetic field for a loss-cone distribution. For electron temperatures in the range 30-100 keV they found that the instability was present for $0.2 \lesssim \omega_{pe}/\Omega_e \lesssim 1.0$. We have conducted a more general analysis which considers emission at all angles to the field and which employs particle simulations as well as linear theory. We find that the radiation is dominated by emission perpendicular to the field and that there is no low-density cutoff to the instability. The low-density instability has been termed[2] the Wu-Lee instability[3], and it is strongest for $kc/\Omega_e \lesssim 1$ and perpendicular emission. In contrast, the azimuthal-bunching instability peaks at k=0 and leads to isotropic emission. The fact that emission in the R-X mode can occur at 90° is a reflection of the important relativistic modifications to the cold-plasma dispersion relation.[4] Particle simulations confirm that the perpendicular emission is dominant and are used to study the saturation mechanism and determine the efficiency of the instability.

* Work supported by USDOE, NSF, and NASA.

1 Y.Y. Lau and K.R. Chu, Phys. Rev. Lett. 50, 243 (1983).
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3 C.S. Wu and L.C. Lee, Astrophys. J. 230, 621 (1979).
4 P.L. Pritchett, Geophys. Res. Lett. 11, 143 (1984).

NONLINEAR RESISTIVE MHD CALCULATIONS IN A POLOIDAL DIVERTOR TOKAMAK WITH THE $q = 1$ SURFACE NEAR THE SEPARATRIX

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In an attempt to understand the physical mechanism which allows $q < 1$ discharges in the Wisconsin Tokapole II,[1] the 3-D reduced resistive MHD code, HIB (provided by PPPL),[2] was used to simulate the internal disruption in a poloidal divertor tokamak with the q=1 surface near the divertor separatrix. For these runs $\beta = 0$ and $S \simeq 1000$, which are similar to the experimental conditions. A circular conducting boundary is used in this code, but equilibrium flux lines are allowed to pass through this boundary. With the q=1 surface located near the divertor separatrix, the amount of helical flux between the q=1 surface and the poloidal divertor separatrix would not permit complete reconnection involving only flux within the separatrix. The code results, however, show that the reconnection proceeds beyond the poloidal divertor separatrix. Code runs with $\eta \sim 1/J_\phi$ show a saturation of the mode before reconnection extends to the original magnetic axis. A code run with constant η, however, exhibited a complete reconnection with the plasma returning to axisymmetry and $q > 1$. The physical mechanism for the saturation in the cases with $\eta \sim 1/J_\phi$ is not understood. This may be an artifact of the initial toroidal current density profile which does not extend beyond the divertor separatrix. A new equilibrium code is being developed to overcome this limitation.[3]

[1] T.H. Osborne, R.N. Dexter and S.C. Prager, Phys. Rev. Lett. 49, 734 (1982).

[2] R. Izzo, et al., Phys. Fluids, 26 2240 (1983).

[3] E. Uchimoto, et al., this conference.

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ON THE THEORY OF PAIRWISE COUPLING EMBEDDED IN MORE GENERAL LOCAL DISPERSION RELATIONS *

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Earlier work on mode conversion theory by Fuchs, Ko, and Bers [1] is detailed and expanded upon, and its relation to energy conservation is discussed. Given a local dispersion relation $D(\omega;\, k, z) = 0$, describing stable waves excited at an externally imposed frequency $\omega = \omega_0$, a pairwise mode-coupling event embedded therein is extracted by expanding $D(k, z)$ around a contour $k = k_c(z)$ obtained from $\partial D/\partial k = 0$. The branch points in z of $D(k, z) = 0$ are the turning points of the potential associated with a second-order differential equation representation for the fields. For real potentials, energy is conserved in each pairwise coupling event. The boundary conditions (incoming, outgoing) are determined by the group velocity $\partial\omega/\partial k$ on each asymptotic branch of k vs. z. Examples occurring in ion-cyclotron and lower-hybrid wave heating are presented, illustrating the use of the method for various boundary conditions.

[1] V. Fuchs, K. Ko, and A. Bers, *Phys. Fluids* 24, 1261 (1981).

* This work was supported in part by DOE Contract No. DE-AC02-78ET-51013 and in part by NSF Grant ECS 82-13430.

Applications of Multi-region Fokker Planck Code to Modeling Tandem Mirrors

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The multi-region Fokker Planck code *MRFP* [1] has been developed for modeling of tandem mirror systems to evaluate the particle distributions in a series of linked square wells. The code is sufficiently versatile to model different arrangements and operating modes of tandem mirror systems and both the ions and electrons can be treated as general, Maxwellian or scalable profile distributions. Relaxations of the distributions in each cell are evaluated locally using the FPPAC [2] code, but the evolution of the passing portion of the distributions are time advanced by bounce averaging through their passages. The self consistent space charge potential in each cell is determined by a dynamic iterative scheme based on ambipolar consideratins. The code is being applied to model a number of tandem mirror configurations and evaluate their performance characteristics. Specific cases of current interest are: (1) simple tandem mirrors with NBI heated plugs in which the electrons in each cell are treated as general species to determine the deviation of the ion confinement potential that can be developed as a function of the plug to center cell density ratio from the Boltzmann well relation due to lack of complete collisional equilibrium of the electrons; (2) thermal barrier tandem mirrors with ions treated as general species and fixed electron distributions to evaluate the depth of the thermal barrier that can be maintained as a function of the neutral beam injection angle and ion pumping arrangements; and (3) Phaedrus tandem mirror with parallel electron heating in the plugs by RF near the ion cyclotron frequency for comparison with the experimentally observed potential enhancement. Results from these computational studies will be presented.

[1] Mehran Baghaii, Ph.D. Thesis under preparation, Rensselaer Polytechnic Institute

[2] M. G. McCoy, A. A. Mirin and J. Killeen, *Computer Physics Communications* **24**, 37 (1981)

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MAGNETIZED RMJ FOKKER-PLANCK EQUATION*

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Several years ago Hassan and Watson[1] derived from the BBGKY hiararchy a kinetic equation for plasmas situated in a uniform external magnetic field. The equation, which is a generalization of Baleseu-Lenard equation, reduces to Rostoker's magnetized kinetic equation[2,3] when the distribution functions are assumed to be independent of azimuthal angles.

The purpose of this note is to show that, for unmagnetized test particles, the complicated collision integral of the equation derived by Hassan and Watson simplifies considerably and can be reduced to the usual RMJ Fokker-Planck form, in which the coefficients of friction and diffusion are velocity derivations of two 'magnetic scalar potentials'. The potentials are evaluated asymptotically in closed form for the case in which collective effects are neglected. The resultant potentials are simple generalizations of Rosenbluth potentials and can easily be used in numerical solutions of the Fokker-Planck equation.

Recently derived magnetized kinetic equations[4] are also discussed and are compared with our results.

1. M.H.A. Hassan and C.J.H. Watson, Plasma Phys. 19 (1977) 237.
2. N. Rostoker, Phys. Fluids 3 (2960) 922
3. N. Rostoker, Nucl. Fusion 1 (1961) 101
4. K. Matsuda, Phys. Fluids 26 (1983) 1508

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Numerical Simulation of Thermal Transport in the TEXT Tokamak*

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Recent power balance calculations[1] using experimental profiles from TEXT have yielded radially resolved profiles for the electron thermal conductivity. These profiles were obtained by assuming electron power balance in the steady state and equating the energy gain through Joule heating to the losses by conduction and exchange with ions (radiation and convection losses were neglected). The resulting expression for the electron thermal diffusivity is then

$$\chi_e(r) = \left(r n_e(r) \frac{\partial T_e}{\partial r} \right)^{-1} \int_0^r (p_{ei} - p_{oh}) r dr$$

where the electrical conductivity is assumed to be Spitzer[2] and the profiles; $n_e(r)$, $T_e(r)$ and $T_i(r)$ are taken from experimental data.

We have performed the equivalent calculation by eliminating the particle and ion energy dynamics in the simulation transport code. By using the appropriate profiles taken from the experimental data base and the previously calculated profile for the electron thermal diffusivity the simulation transport code generates the expected steady state situation. We also find that a steady state may be obtained by replacing the measured quantity with an empirical expression given by Coppi and Mazzucato[3]. The steady state result is obtained by choosing the numerical coefficient ϵ_D to be $.388 \times 10^{-2}$ which is within 25% of the value given in Ref. 3.

Since the experimental data for the ion temperature profile, the particle flux and the radiation are not yet complete, these effects may be simulated by retaining the particle and ion energy dynamics in the transport code in order to complete the analysis. Results of these calculations will be reported.

1. R. V. Bravenec, D. L. Brower, K. W. Gentle, T. P. Kochanski, N. C. Luhmann, Jr., W. A. Peebles, P. E. Phillips, B. Richards, W. L. Rowan, J. C. Wiley, and C. X. Yu, Bull. Am. Phys. Soc. **28**, 1033 (1983).
2. L. Spitzer, Jr. and R. Hãrm, Phys. Rev. **89**, 977 (1953).
3. B. Coppi and E. Mazzucato, Phys. Lett. **71A**, 337 (1979).

*Work supported by U. S. Department of Energy contract #DE-AC05-76ET 53036

Incorporation of Time Dependent 2-d MHD Equilibrium Flux Surface Geometry in the TRANSP Transport Analysis Code. D.C.MCCUNE, R.J.GOLDSTON, R.T.MCCANN, Princeton U.* The TRANSP code has been generalized to permit analysis of tokamak experiments (e.g. PBX, TFTR compression) with time-varying geometry. Experimental data provide temperature and density profiles, plasma current and surface voltage, external toroidal field, and position and shape of the outermost flux surface of the plasma, all as functions of time. The TRANSP code calculates q, and perpendicular and parallel pressure profiles which are passed to an MHD equilibrium routine. In the MHD calculation the q and pressure profiles at the start of a "geometrical timestep" are coupled with the outermost flux surface shape measured at the end of the timestep, and the resulting interior flux surfaces are assigned to the end of the timestep. Then, for the duration of the geometrical timestep, the flux surface shapes and their time rate of change may be defined for the transport code. Transport and poloidal field diffusion equations are solved in this time evolving grid, with the toroidal flux enclosed by the defined "plasma" allowed to vary in time. Plasma particle and energy transport are deduced from the input diagnostic data. Other diagnostics (not directly input) are simulated as a check.

Examples from a TFTR compression shot, using a Shafranov (shifted circular) MHD equilibrium, will be presented.

Studies are under way to select a fast, accurate (probably moments expansion) MHD equilibrium package to interface to TRANSP.

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CURRENT RAMP-UP IN LOWER HYBRID CURRENT DRIVE EXPERIMENTS*

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The radial time-dependent transport code ONETWO[1] has been modified to include the effects of a self-consistent profile of radio frequency wave induced current, acting as a source in Ampère's equation. The rf deposition profile is found from a 1-D quasilinear model of lower hybrid electron damping. Temporal evolution of the rf current is determined and compared with recent PLT experiments. The induced toroidal electric field introduces interesting new features into the study, such as possible production of runaway electrons in the negative rf current direction, and reduced current drive efficiency. These effects are discussed with respect to both the PLT and reactor regimes.

[1] W.W. Pfeiffer *et al.,* GA Technologies Report GA-A16178 (1980).
*Work supported by U.S. DOE Contract DE-AT03-84ER53158.

Large Wavelength Ballooning Modes in a Linear Multipole*

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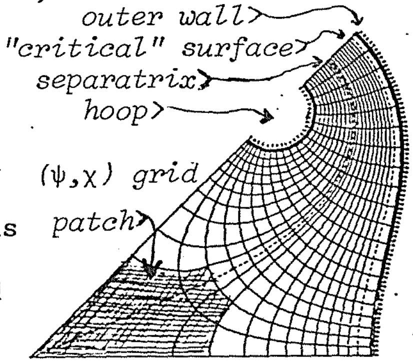
This poster reports the progress of a numerical investigation into arbitrary wavelength ballooning modes. This research was prompted by measurements in the Wisconsin Large Octupole of pressures far higher than had been predicted on the basis of localized MHD theory.[1]

Multipoles are particularly interesting devices in which to study ballooning modes. A multipole contains flux surfaces of all average well depths, from zero (at the "critical" flux surface, where the interchange mode becomes unstable) to infinity (at the separatrix, where the central field null effectively anchors field lines). With no shear, the small wavelength MHD analysis is especially easy to carry out and interpret. A ballooning mode is a series of vortex cells aligned along field lines. As the mode grows, it twists and winds up most in the region of bad curvature. In the asymptotic small wavelength, the vortex cells are long and narrow (extent across flux surface >> wavelength).

Consider a sequence of pressure profiles characterized by increasing peak pressure. For some pressure, a single flux surface becomes unstable to the asymptotically localized mode; for higher pressures, the mode structure extends over a larger region. The marginally stable MHD equations form, for each equilibrium in the sequence, an eigenvalue problem for the wavelength of the marginally stable mode. The goal of this project is to solve this eigenvalue problem, without any approximations based on the large wavenumber (1/k) expansion, whether the mode is highly localized or has global extent.



A MHD equilibrium is numerically found on an orthogonal curvilinear grid (flux coordinates). Being singular at the origin, this grid must be patched there -- a harmonic series representation of ψ is used. Such a grid is shown at right for one eighth of an octupole. A four step process is used, involving an intermediate solution of the Grad-Schafranov equation on a Cartesian grid, and finishing with an iterative solution on the flux coordinate grid as the grid settles down. Grid lines may be concentrated in the region of instability.

The marginally stable eigenvalue problem is a coupled set of PDEs in ξ_ψ and ξ_z. This may be reduced to a single fourth order PDE in ξ_ψ by an ordering in the ratio of changes parallel and perpendicular to the magnetic field. A converging numerical method has been found for this reduced problem, which can hopefully be bootstrapped into a solution for the full problem.

The stabilizing effect of large gyroradius can be crudely modeled by a sharp cutoff of the MHD spectrum at some k, where $k\rho_i \simeq 1$. Some physical arguments will be given which suggest greater stability at larger wavelengths, in terms of a gradient in average well depth, and the shape of the vortex cells.

1) A.G. Kellman, M.W. Phillips, C.C. Prager & M.C. Zarsntorff, Nuclear Fusion, 23, 1561 (1983)

*) Supported by U.S. Department of Energy & National Science Foundation

ARE MAJOR DISRUPTIONS CAUSED BY VACUUM "BUBBLES"?*

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Tearing modes with m/n = 2 are shown to grow to very large amplitude when the safety factor on axis q(0) $\gtrsim$ 1.5, the magnetic island associated with the mode encompassing virtually the entire plasma cross section. These very large magnetic islands are shown to be related to the vacuum "bubbles" created during the nonlinear evolution of the ideal 2/1 kink mode. When q(0) = 1.3, the island is found to saturate benignly at a width w ~ 0.4a, consistent with previous investigations ["a" is the radius of the cylinder]. However, as q(0) rises the difference in the pitch of the q = 2 islands and the magnetic field lines in the center of the column decreases and the magnetic tension created as the mode grows is insufficient to stop the instability. As a result, the island grows to nearly the center of the column squashing the current into a narrow bar between the inner separatrices before bouncing back. The rapid loss of energy which would result from the formation of such large islands is proposed as a mechanism for major disruptions. If this mechanism is correct, then an obvious method for eliminating major disruptions is to strongly heat the center of the plasma thereby driving q(0) down.

*Work supported by the U.S. Department of Energy.

Equilibrium Studies for Helical Axis Stellarators*

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The equilibrium properties of helical axis stellarator configurations have been studied with the 3-D NEAR code[1] and by an average method.[2] Two sequences of heliac configurations with a given ratio of number of field periods to aspect ratio have been studied. Heliacs with a relatively small aspect ratio and number of field periods, which have a toroidally dominated shift, are found to have a low equilibrium beta limit. More favorable results are found at larger aspect ratio and field periods. The effects on the equilibria of modulating the currents in the toroidal field coils and by winding the toroidal field coil axis as a geodesic on a torus are being studied.

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[1]T. C. Hender, et al., Bull. Am. Phys. Soc. 27 (8) 1020 (1982).
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A ONE-DIMENSIONAL TRANSPORT CODE FOR FIELD-REVERSED CONFIGURATIONS

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A radial transport code for Field-Reversed Configurations (FRCs) is described. Assuming quasi-neutrality and neglecting inertia, the evolution of particle densities, temperatures, and magnetic field through a series of equilibrium states is simulated. To solve the equations, transformations of all dependent variables and one independent variable are carried out. The processes of interest can be decoupled into two distinctive sets of equations that describe adiabatic and nonadiabatic processes. These sets of equations are then solved by two alternating steps: adiabatic and nonadiabatic. (This is one kind of splitting method.)

Important features of the present formalism (several transformations) include the following:

1. The independent variable is a type of flux variable whose interval is fixed. This is especially convenient for numerical treatment. In terms of this variable all equations are regular in the whole interval. The new dependent variables are adiabatic invariants of the ideal MHD system and evolve in time due to all forms of dissipation. Axial contractions and radial compressions (either wall compression or change of vacuum magnetic field) can be simulated.

2. Although the code is one-dimensional (all quantities can vary only in the radial direction), total axial force balance is incorporated.

3. Many physical processes, e.g., impurity radiation, Joule heating, etc. can be included, which represent various source terms for particle densities or energies.

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ICRF STABILIZATION OF INTERCHANGE MODES

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We calculate the effects of RF fields in the ion cyclotron frequency range on the stability of electrostatic interchange modes using the two fluid plasma equations. The results show that ICRF can be used to fully stabilize interchanges without invoking ponderomotive forces, if certain conditions are satisfied. Stability conditions will be presented and applied to experiment, e.g., to the Phaedrus tandem mirror experiment, in which ICRF stabilization of interchange modes has been observed [1].

References:

1. J. R. Ferron et al., Phys. Rev. Lett 51, 1955 (1983).

A NUMERICAL METHOD FOR CONSTANT-ψ TEARING MODES*

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A set of equations is developed for the inner layer of tearing modes which takes advantage of the constant-ψ approximation. This reduced set of equations has the feature that the higher-node shear Alfvén waves are eliminated from the system, in much the same way that the magnetosonic wave is eliminated from the usual reduced equations. The resulting equations are especially suited for use in nonlinear, initial-value inner-layer-tearing mode codes as the time step is no longer restricted by the Courant condition [$\tau < (k_{\parallel} v_A)^{-1}$]. Since tearing rates of change are slower than shear Alfvén frequencies by some fractional power of S, the Lundquist number, the time savings in a numerical solution of the problem can be considerable. Representative cases of linear and nonlinear tearing mode evolution will be presented which compare the use of the constant-ψ equations with the usual equations. Extensions to the semi-collisional and drift-tearing regimes will be examined. Limitations of the method, especially for broad inner layers, will be set forth, and the possibility of matching to an outer region code will be discussed.

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