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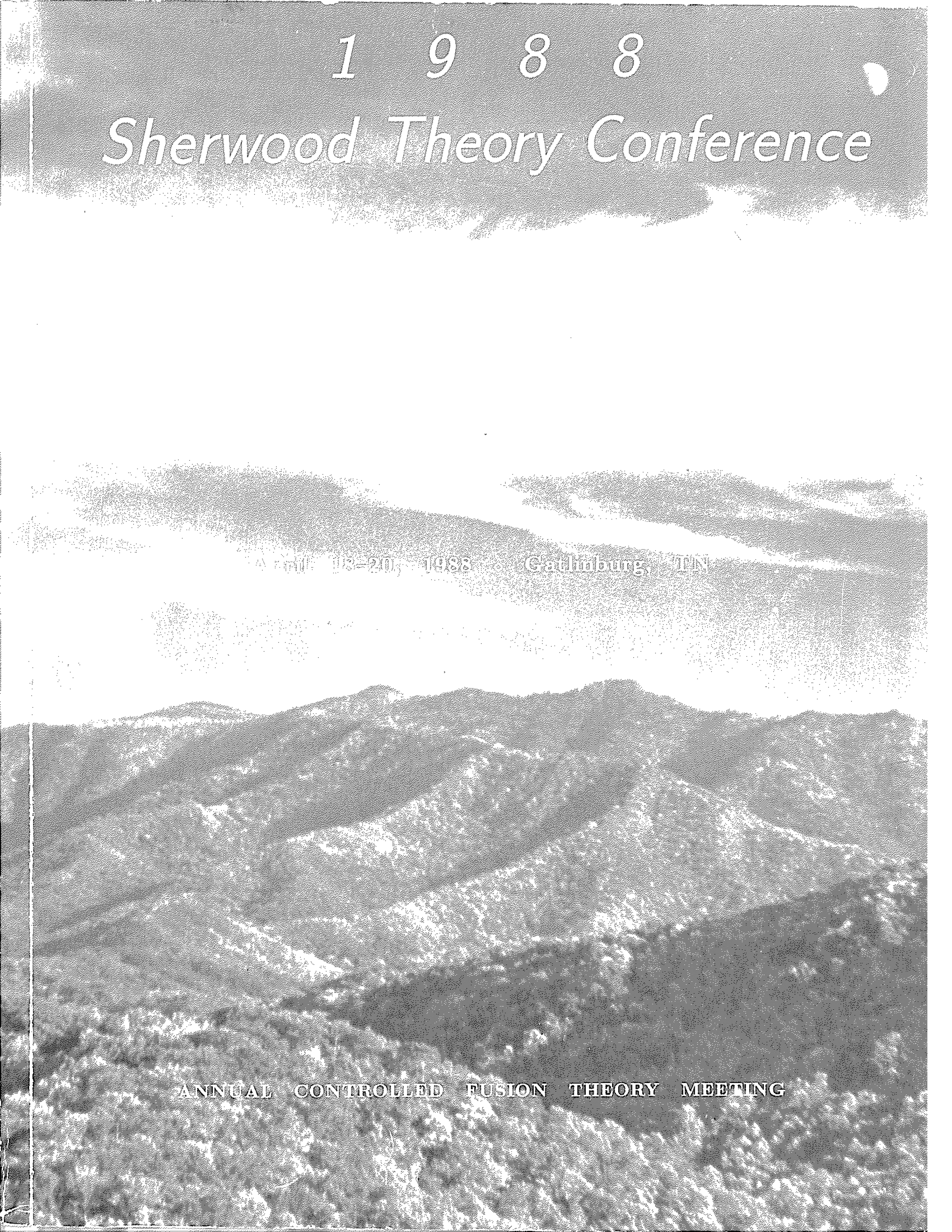
Sherwood Theory Conference



April 18–20, 1988 • Gatlinburg, TN

ANNUAL CONTROLLED FUSION THEORY MEETING

Saralyn Stewart

1988
Sherwood Controlled Fusion Theory Conference

April 18-20, 1988
Holiday Inn—Gatlinburg
Gatlinburg, Tennessee

Under the auspices of
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Executive Committee

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C. Adams
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C. L. Hedrick
M. Hutchinson
B. Sarfaty
S. Stewart

General Information

* 242 papers were submitted, of which 12 were selected for oral presentation.

* The Review papers will be presented in the Greenbriar Room, Monday and Tuesday mornings beginning at 8:30 a.m.

* All oral papers will be presented in the Greenbriar Room, Monday and Tuesday mornings beginning at 9:30 a.m. Each talk will be 25 minutes in length plus 5 minutes for discussion.

* A special session on Space and Astrophysical Plasmas will be held on Tuesday afternoon beginning at 2:00 p.m. in the Greenbriar Room.

* Poster sessions will be held in the Gatlinburg/Glades/Leconte Rooms, Monday afternoon, Tuesday evening, and Wednesday morning.

* A barbeque will be held on Monday evening, 6:30–8:30 p.m. at Mynatt Park. Please sign-up for this event at the Conference Registration Desk (in case of rain it will be moved to the Greenbriar Room).

* Refreshments will be served consisting of coffee and tea during the morning sessions; beer and soft drinks during the afternoon and evening sessions; on Tuesday afternoon there will be coffee and iced tea.

* Information can be obtained from the Conference Registration Desk regarding local sights, restaurants, and transportation.

* Requests for special meetings should be made with Gail Hamilton at the Conference Registration Desk.

* Requests to visit the Oak Ridge National Laboratory should be made at the Conference Registration Desk.

1988 SHERWOOD THEORY CONFERENCE SCHEDULE
HOLIDAY INN–GATLINBURG
APRIL 18-20, 1988

Registration

April 17, 1988 — 6:00 - 10:00 PM
April 18-19, 1988 - 7:45 AM - 5:00 PM
April 20, 1988 - 8:30 AM - 1:00 PM
Highrise Lobby

Oral and Poster Session Schedule

Reviews and Orals - Greenbriar Room
Posters - Gatlinburg/Glades/Leconte Rooms

Monday, April 18, 1988

Welcome - 8:15 AM
1A — 8:30 AM — Review Paper
1B — 9:30 AM - 12:30 PM — Oral Session
12:30 - 2:00 PM — LUNCH BREAK
1C — 2:00 - 4:00 PM — Poster Session
1D — 4:00 - 6:00 PM — Poster Session
6:30 - 8:30 PM — BARBEQUE

Tuesday, April 19, 1988

2A — 8:30 AM — Review Paper
2B — 9:30 AM - 12:30 PM — Oral Session
12:30 - 2:00 PM — LUNCH BREAK
2S - 2:00 - 5:00 PM — Special Session
5:00 - 7:00 PM — DINNER BREAK
2C — 7:00 - 9:00 PM — Poster Session
2D — 9:00 - 11:00 PM — Poster Session

Wednesday, April 20, 1988

3C — 9:00 - 11:00 AM — Poster Session
3D — 11:00 AM - 1:00 PM — Poster Session

Coffee and Tea - 10:00 AM, Monday through Wednesday
Beer and Soft Drinks - 3:00 PM, Monday; 8:00 PM, Tuesday
Coffee and Iced Tea - 3:00 PM, Tuesday

1988 SHERWOOD THEORY CONFERENCE
ANNUAL CONTROLLED FUSION THEORY CONFERENCE

Holiday Inn - Gatlinburg
Gatlinburg, Tennessee
April 18 - 20, 1988

MONDAY REGISTRATION 7:45am - 5:00pm

MONDAY MORNING 8:30am - 12:30pm

WELCOME 8:15am

1A REVIEW SESSION
8:30am Greenbriar Room
Presiding: Cloyd Beasley

1A1. The Experimental Bootstrap Current. M. Zarnstorff.

1B ORAL SESSION
9:30am Greenbriar Room
Presiding: Richard Gerwin

1B1. Neoclassical MHD Effects on Pressure-Gradient Driven and Tearing Instabilities. D. A. Spong, K. C. Shaing, B. A. Carreras, and J. D. Callen.
1B2. Streamer Formation in Plasma with a Temperature Gradients. J. F. Drake, P. N. Guzdar, and A. B. Hassam.
1B3. Dynamics and Fluctuation Spectrum of Ion Temperature Gradient Driven Instabilities in a Sheared Magnetic Field with Multiple Rational Surfaces. R. D. Sydora, W. W. Lee, T. S. Hahm, and J. M. Dawson.
1B4. Rising Bucket Current Drive. R. H. Cohen, T. D. Rognlien, G. R. Smith, and B. I. Cohen.
1B5. Quasi-Helically Symmetric Toroidal Stellarators and Neoclassical Transport Calculations for Helias and Quasi-Helically Symmetric Stellarators. J. Nuhrenberg, R. Zille, and W. Lotz.
1B6. Minimum-Dissipation States and the RFP. D. Montgomery and L. Phillips.

LUNCH 12:30 - 2:00pm

MONDAY AFTERNOON 2:00 - 6:00pm

1C POSTER SESSION
Gatlinburg, Glades, LeConte Rooms
2:00 - 4:00pm

1C1. The Liouville Equation and the Study of Two-dimensional MHD Equilibria. A. J. Neil and E. R. Tracy.
1C2. A Model of Intermittent Turbulence in Compressible Self-Gravitating Gas and Vlasov Plasma. P. H. Diamond and H. Biglari.
1C3. Self-Similar, Ohmic Ramp Down of RFP Equilibria. E. J. Caramana, R. A. Nebel, J. A. Phillips, D. A. Baker, R. F. Gribble, and C. P. Munson.

1C4. Electron Cyclotron Heating and Current Drive in ITER. G. R. Smith, A. W. Molvik, and A. H. Kritz.
1C5. Nonlinear Mechanisms for Drift Wave Saturation and Induced Particle Transport. A. M. Dimits, W. W. Lee, and R. D. Sydora.
1C6. Suppression of Sawtooth Oscillations in Plasmas with High Energy Particle Populations. P. Detragiache, B. Coppi, R. J. Hastie, F. Pegoraro, and F. Porcelli.
1C7. Nonlinear Consequences of m=1 Evolution in Toroidal Geometry. J. A. Holmes, B. A. Carreras, L. A. Charlton, and V. E. Lynch.
1C8. Nonlinear Density and Potential Modifications Induced in the Edge Plasma by High Power ICRF Antennas - II. Collisional Theory. J. R. Myra and D. A. D'Ippolito.
1C9. Nonlinear Density and Potential Modifications Induced in the Edge Plasma by High Power ICRF Antennas - I. Collisionless Theory. D. A. D'Ippolito and J. R. Myra.
1C10. Comparison of Particle Orbits in Both Boozer Coordinates and Real Space Coordinates. R. N. Morris, R. H. Fowler, J. A. Rome, and S. P. Hirshman.
1C11. Ballooning Modes in Low Shear Tokamaks. M. W. Phillips.
1C12. Upper and Lower Bounds for Transport Coefficients in 3-D Toroidal Systems. W. I. Van Rij and S. P. Hirshman.
1C13. Non-stability of Low q Profile in Tokamaks at Zero Beta. R. E. Denton, J. F. Drake, and R. G. Kleva.
1C14. Stabilization of Ballooning Modes by Flow. S. T. Chun and E. Hameiri.
1C15. Tokamak Collisional Transport Theory Near the Separatrix. A. Nocentini.
1C16. Study of Pressure Gradient Modes in Finite Beta Plasmas. B. G. Hong, W. Horton, and D. I. Choi.
1C17. Ballooning Stability Environment in Arbitrary Tokamak Equilibria. M. S. Chance, M. S. Chu, J. M. Greene, L. Lao, and T. C. Simonen.
1C18. Profile Consistency, Heat Pulse Propagation, and Nonlinear Thermal Transport. R. Englade and B. Coppi.
1C19. Relaxation of the High Density Z-Pinch to Self-Similar Behavior in the Presence of Inertia and Viscosity. A. H. Glasser.
1C20. Resistive g-Mode Steady Convection and Heat Transport. S. Hamaguchi, E. Hameiri, and H. R. Strauss.
1C21. Effect of Partial Reconnection Sawtooth Model in Transport Simulations. G. Bateman, D. P. Stotler, and W. Stodiek.
1C22. Internal Kink Modes in Shaped Tokamaks. J. Manickam, C. Z. Cheng, B. Coppi, and A. E. Miller.
1C23. Ion Transport Theory Constraints on Linear Offset Scaling for tau(E). D. J. Sigmar and C. T. Hsu.
1C24. The Effect of Finite Pressure on Saturated Tearing Modes. J. S. McCauley and G. Bateman.
1C25. Particle Simulation of Toroidicity-Induced Drift Modes. M. J. LeBrun and T. Tajima.
1C26. 1-D Modeling of Mode Beating OFCD in a Tokamak. D. Herbison.
1C27. Growth Rates of Resistive Ballooning Modes in Tokamaks Near the Beta Limit. H. P. Zehrfeld and K. Grassie.
1C28. Ideal MHD Stability Marginal Points in TJ-II. A. Varias.
1C29. Heating of Solar Corona. P. L. Similon and R. N. Sudan.
1C30. Sawteeth. M. Theobald, D. Montgomery, G. Doolen, and J. P. Dahlburg.
1C31. Decimation of the Betchov Model of Turbulence. T. Williams, E. R. Tracy, and G. Vahala.
1C32. A Fluid Ions-Particle Electrons Model for Plasma Instabilities. P. M. Lyster and J. N. Leboeuf.
1C33. Fast Equilibrium Calculations. S. W. Haney and J. P. Freidberg.
1C34. Asymptotic Calculation of the Geometric Phase in Classical Mechanics. T. Sen and A. Bhattacharjee.
1C35. Tokamak Transport in the Presence of Multiple Mechanisms. J. Sheffield.
1C36. Mode Conversion in the Presence of Dissipation for Heating in ICRF. V. Fuchs and A. Bers.
1C37. Almost Two-dimensional Drift Wave Turbulence. J. M. Albert, P. L. Similon, and R. N. Sudan.

1D POSTER SESSION
Gatlinburg, Glades, LeConte Rooms
4:00 - 6:00pm

1D1. ICRF Wave Propagation through the Turbulent Edge. A. N. Kaufman and D. R. Thayer.
1D2. Electromagnetic Effects in the Detection of Alpha Particles in Millimeter Scattering. L. Vahala, G. Vahala, and D. J. Sigmar.
1D3. TOK3D: A Model for 3d Resistive MHD Computations in Toroidal Geometry. D. S. Harned and D. C. Barnes.
1D4. Parameterization of the High-n Second Region of Ideal MHD Stability in Circular Boundary Tokamaks. S. A. Sabbagh, M. W. Phillips, A. M. M. Todd, and G. A. Navratil.
1D5. Particle Simulations of Low Frequency Fluctuations in Finite Beta Plasmas. J. H. Han and J. N. Leboeuf.
1D6. Forced Alfven Wave Turbulence and Subgrid Scale Closure. Y. Zhou and G. Vahala.
1D7. The Enhancement of Ion Neoclassical Heat Conduction Due to Electron and Beam-Ion Energy Scattering Collisions. A. A. Ware.
1D8. Numerical Studies of RF Current Profile Control in Low Aspect Ratio, High Beta Tokamaks. P. T. Bonoli and M. Porkolab.
1D9. Limitations on Aspect Ratio, q(o), and q(a) Required for Stable Access to Second Stability in Tokamaks. M. J. Gerver, J. Kesner, J. J. Ramos, and S. P. Hakkarainen.
1D10. Exact Solutions of the Vlasov-Maxwell System. S. M. Mahajan.
1D11. Toroidal Semicollisional Microinstabilities and Anomalous Electron and Ion Transport. F. Romanelli and S. Briguglio.
1D12. A Survey of Direct Linear Systems Solvers on the NMFECC System. A. A. Mirin, D. V. Anderson, M. G. McCoy, and S. W. White.
1D13. Three-Dimensional Equilibrium Studies of an Unconventional Stellarator Design. A. Salas and A. H. Reiman.
1D14. Transport and Stability Considerations for the MICF Reactor. T. Kammash and D. L. Galbraith.
1D15. The Magnetic Field Lines on a Perfect Conductor or Circle Maps Generated by the Neumann Problem in a Torus. P. J. Morrison and J. D. Meiss.
1D16. Statistical Analysis of ASDEX Ohmic Profiles. P. J. McCarthy, K. S. Riedel, O. Gruber, O. Kardaun, and K. Lackner.
1D17. Nonlinear Evolution of a Force-Free Arcade Field Driven by Shear Flow. N. Bekki, T. Tajima, J. W. Van Dam, Z. Mikic, D. C. Barnes, and D. D. Schnack.
1D18. A Linearized Resistive MHD Stability Code. T. R. Harley, C. Z. Cheng, and S. C. Jardin.
1D19. Transport and ICRF Modelling in CIT with Magnetic Field Ramp. J. S. Tolliver, S. E. Attenberger, W. A. Houlberg, D. B. Batchelor, and C. K. Phillips.
1D20. Toroidal 3-D MHD Simulation. W. Park and D. A. Monticello.
1D21. Neutral Transport in a Time-Dependent Plasma Modelling Code Using the Multigroup Diffusion Approximation. T. B. Kaiser.
1D22. On the Connection Between Micro- and Macrostability and Sawtooth Oscillations in Tokamaks. C. Litwin.
1D23. Electron Transport Near a Separatrix and the H-Mode. G. M. Staebler and F. L. Hinton.
1D24. Ion Heat Flow in a Model Divertor Configuration. F. L. Hinton.
1D25. Magnetic Flux Loss in a Field Reversed Configuration. A. G. Sgro.
1D26. Production of Non-Thermal Electrons by Electron Cyclotron Heating in ATF. C. Alejaldre, F. Castejon, and V. Krivenski.
1D27. Ideal Low-n and Mercier Stability Boundaries for l=2 Torsatrons. N. Dominguez, J. N. Leboeuf, B. A. Carreras, and V. E. Lynch.
1D28. Effect of Density Fluctuations on ICRF Heating of Tokamaks. H. Romero and G. J. Morales.
1D29. Heating of Two-Component Plasma in the Fundamental Minority Cyclotron Range of Frequencies. W. Q. Li, D. W. Ross, and S. M. Mahajan.
1D30. Predictions of the Ion Temperature Gradient eta(i) Mode in the Columbia Linear Machine. O. Mathey and A. K. Sen.
1D31. Magnetic Fluctuations Due to Thermally Excited Alfven Waves. Y. Z. Agim and S. C. Prager.
1D32. Poloidal Field Effects on ICRH in Large Tokamaks. K. Imre, D. C. Stevens, H. Weitzner, and D. B. Batchelor.

1D33. Simulation of Collisionless Magnetic Reconnection with Realistic Ion to Electron Mass Ratio. G. E. Francis, D. W. Hewett, and C. E. Max.
1D34. Sensitivity of Transient Synchrotron Radiation to Tokamak Plasma Parameters. A. H. Kritz and N. J. Fisch.
1D35. Transport in a Moderately Large Aspect Ratio, Near Circular Cross Section Tokamak. H. Weitzner.
1D36. Simulation of Toroidicity in a Linear Heliac. D. C. Barnes, F. L. Ribe, and B. A. Nelson.
1D37. Resistive Infernal Modes. L. A. Charlton, R. J. Hastie, and T. C. Hender.

BARBEQUE 6:30pm

TUESDAY MORNING 8:30am - 12:30pm

2A REVIEW SESSION
8:30am Greenbriar Room
Presiding: Jim Drake

2A1. Chaos, Strange Attractors, and Fractal Basin Boundaries in Nonlinear Dynamics. E. Ott.

2B ORAL SESSION
9:30am Greenbriar Room
Presiding: Doug Harned

2B1. Sawtooth Stabilization in the Presence of Energetic Ions. F. Pegoraro, F. Porcelli, and R. J. Hastie.
2B2. Sawtooth Stabilization by Energetic Trapped Particles/Energetic Particle Stabilization of Kink Modes in Tokamaks. R. B. White, P. H. Rutherford, P. Colestock, M. N. Bussac, and C. Z. Cheng.
2B3. Toroidal Studies of Sawtooth Oscillations in Tokamaks. A. Y. Aydemir, D. W. Ross, and J. C. Wiley.
2B4. Theoretical Understanding of JET MHD Behavior. J. A. Wesson.
2B5. Destabilization of Ballooning Modes by Sheared Equilibrium Flows in Axisymmetric Plasmas. A. Bhattacharjee, R. Iacono, J. Milovich, and C. Paranicas.
2B6. Thermally Driven Convective Cell Edge Turbulence: Theory and Experiment. D. R. Thayer, P. H. Diamond, Ch. P. Ritz, and A. J. Wootton.

LUNCH 12:30 - 2:00pm

TUESDAY AFTERNOON 2:00 - 5:00pm

2S SPECIAL SESSION - Space and Astrophysical Plasmas
Presiding: Chuan Liu
Break from 3:00-3:15pm

2S1. The Formation of Sunlike Stars. F. H. Shu.
2S2. Numerical MHD and Plasma Physics Applied to Problems in Astrophysics. M. Norman.
2S3. Stellar X-Rays, the Solar Corona, and Spontaneous Magnetic Discontinuities. E. N. Parker.
2S4. On the Physics of Collisionless Shock Waves. K. Papadopoulos.
2S5. Ionospheric F-Region Irregularities. S. L. Ossakow and J. D. Huba.
2S6. Activity at Barium Clouds in Space. D. Winske.

TUESDAY EVENING 7:00 - 11:00pm

2C POSTER SESSION
Gatlinburg, Glades, LeConte Rooms
7:00-9:00pm

2C1. Profile Consistency and Beta Limit Disruptions from Resistive MHD. M. Hossain and H. R. Strauss.
2C2. Tearing Mode Stability of the Most Probable Profile. J. Y. Hsu and M. S. Chance.
2C3. Theoretically Based Transport Models: Simulation. J. C. Wiley, D. W. Ross, and W. H. Miner.
2C4. Theoretically Based Transport Models: Analysis. D. W. Ross, P. W. Terry, J. C. Wiley, and W. H. Miner.
2C5. The Empirical Tokamak: Confidence Limits on Estimated Model Parameters. W. H. Miner, D. W. Ross, and J. C. Wiley.
2C6. Destabilization of the Toroidal Discrete Shear Alfven Wave by Alpha Particles in an Ignited Tokamak. G. Y. Fu, J. W. Van Dam, and M. N. Rosenbluth.
2C7. A Finite-Banana-Width, Bounce-Averaged, Fokker Planck Operator for Tokamaks-Applications to Neoclassical Transport Theory. G. P. Tomaschke, G. D. Kerbel, and M. G. McCoy.
2C8. New Features of the NMFECC Fokker-Planck Facility CQL(02). G. D. Kerbel and M. G. McCoy.
2C9. Developments in the Theory of Ion Temperature Gradient Turbulence in Tokamaks. N. Mattor and P. H. Diamond.
2C10. The High Frequency Hot Electron Interchange Mode in a Cylindrical Hollow Pure Hot Electron Plasma. J. E. Sedlak, Y. Z. Zhang, and H. L. Berk.
2C11. Fokker-Planck Simulation of a Migma Reactor. C. Powell, M. Kress, and A. Wilmerding.
2C12. Transport and Stability of Z Pinch Fibers. P. Sheehey, P. Rosenau, R. A. Nebel, and I. R. Lindemuth.
2C13. RFP Behavior with a Resistive Wall. H. R. Strauss.
2C14. Study of the Current Sheet in a Field Reversed Configuration. I. Doxas, W. Horton, K. Sandusky, T. Tajima, and R. Steinolfson.
2C15. Magnetic Surface Destruction by Ion Cyclotron Frequency Radiation. J. A. Tataronis and C. Litwin.
2C16. Properties of eta(i) Instabilities in H-Mode Plasmas. W. M. Tang and T. S. Hahm.
2C17. Nonlinear Evolution of Ion Temperature Gradient Driven Instabilities and the Associated Thermal Transport. T. S. Hahm, W. W. Lee, and R. D. Sydora.
2C18. BETAS, A Spectral Code for Three Dimensional Magnetohydrodynamic Equilibrium and Nonlinear Stability Calculations. O. Betancourt.
2C19. Simulation of Beam Driven Currents in Tokamaks. S. E. Attenberger, W. A. Houlberg, and N. A. Uckan.
2C20. Radial Particle Fluxes and the Bootstrap Current in an ATF-like Stellarator Reactor. W. D. D'Haeseleer, W. N. G. Hitchon, and J. L. Shohet.
2C21. Toroidal Ion-Pressure-Gradient-Driven Drift Instabilities and Transport Revisited. H. Biglari and P. H. Diamond.
2C22. Effect of Temperature Gradients on Dissipative Trapped Ion Mode. M. N. Rosenbluth.
2C23. On the Theoretical Foundations of the Troyon-Sykes Scaling. J. J. Ramos.
2C24. Three Dimensional Gyrokinetic Particle Simulation Model for Studying Low Frequency Fluctuations in Tokamaks. H. Naitou, R. D. Sydora, W. W. Lee, T. S. Hahm, and J. M. Dawson.
2C25. Fueling and Current Drive with Compact Toroids in a Steady-State Tokamak Reactor. W. M. Nevins.
2C26. Investigations of Nonlinear Semicollisional Magnetic Islands in a Torus. M. Kotschenreuther.
2C27. Calculation of Neutral Beam Current Drive in the Presence of Alfven Wave Turbulence. R. B. Campbell.
2C28. Explicit Evaluation of the Generalized Balescu-Lenard Collision Operator. R. E. Duvall and H. E. Mynick.
2C29. Fast Current Penetration in Expanding Tokamaks. N. Pomphrey and S. C. Jardin.
2C30. Resistive Fluid Turbulence Induced Transport and Radial Electric Field. G. S. Lee, B. A. Carreras, and K. C. Shaing.
2C31. Nonlinear MHD Simulation of an RFP Nonideal Boundary Condition. Y. L. Ho, S. C. Prager, and D. D. Schnack.

2C32. Coupling Theory of RF Waves with Resonant Loop Antennas in Tokamaks. G. L. Chen.
2C33. Study of Turbulent Transport Due to Drift-Alfven Fluctuations. A. A. Thoul, P. L. Similon, and R. N. Sudan.
2C34. Effects of Radio-Frequency Fields on Transport. S. C. Chiu and V. S. Chan.
2C35. A Universal Concurrent Algorithm for Plasma Particle-in-Cell Simulation Codes. P. C. Liewer, V. K. Decyk, J. M. Dawson, and G. C. Fox.
2C36. Stability Analysis of High Beta Poloidal Discharges in the Versator II Tokamak. B. G. Lane, J. Kesner, S. Luckhardt, and K. Chen.
2C37. Necessary Equilibrium Conditions for Advanced Toroidal Experiments. F. J. Helton and J. M. Greene.

2D POSTER SESSION
Gatlinburg, Glades, LeConte Rooms
9:00-11:00pm

2D1. Low Beta Stability of the DIII-D Tokamak. A. D. Turnbull, F. J. Helton, M. S. Chu, L. Lao, A. G. Kellman, W. Howl, and T. H. Osborne.
2D2. Nonlinear Saturation of Ballooning Modes in Stellarators. F. Bauer, O. Betancourt, and P. Garabedian.
2D3. Plasma Sheaths and Impurity Genertion by ICRF Antennas. F. W. Perkins.
2D4. Relation Between Beam Driven Seed-Current and Rotation in Steady State FRC. M. Okamoto, H. L. Berk, and J. H. Hammer.
2D5. Over Focusing in the Migma Configuration. H. L. Berk and H. V. Wong.
2D6. Stability of Energetic Ring Equilibrium of Large Orbit Ions. R. V. Lovelace, H. L. Berk, N. Rostoker, and H. V. Wong.
2D7. Orbit Stochasticity and Radial Diffusion. J. D. Meiss and R. D. Hazeltine.
2D8. Rigorous Upper Bounds for Passive Turbulent Advection. J. A. Krommes and C.-B. Kim.
2D9. Quasilinear Evolution of the Mean Poloidal Magnetic Flux in a Tokamak Due to Tearing Mode Turbulence. C.-B. Kim, J. A. Krommes, and J. M. Finn.
2D10. Averaging of Nonlinear Wavetrains. J. W. Larson and E. R. Tracy.
2D11. Numerical Simulation of Tearing Modes in a Tokamak. R. H. Weening.
2D12. Stochastic Electron Cyclotron Heating for Current Drive. T. D. Rognlien, R. H. Cohen, and W. M. Nevins.
2D13. Alfven Wave Propagation and Absorption with Linetied Boundary Conditions. W. Lawson, H. R. Strauss, and N. Otani.
2D14. Hyper-Resistivity of Very Densly Packed Tearing Mode Turbulence. G. Craddock.
2D15. The Role of m=0 Modal Components in the RFP Dynamo Under the MHD Model. R. A. Nebel, E. J. Caramana, and D. D. Schnack.
2D16. MHD Studies of the Tilt Mode in a Field-Reversed Configuration. R. D. Milroy, D. C. Barnes, R. C. Bishop, and R. B. Webster.
2D17. Simulation of Driven 2-D Microtearing Mode Turbulence. X. N. Su and P. W. Terry.
2D18. Linear and Nonlinear Simulations of Resistive MHD Instabilities in a Poloidal Divertor Tokamak. E. Uchimoto, Z. Chang, J. D. Callen, and S. C. Prager.
2D19. Axisymmetric Stability Studies of Tokamak Plasmas. R. Weiner, S. C. Jardin, and N. Pomphrey.
2D20. Fokker-Planck Code for Current Drive in Tokamak. Y. Matsuda and L. D. Pearlstein.
2D21. Spherical Harmonic Expansion for the Relativistic Collision Operator. C. F. F. Karney and B. J. Braams.
2D22. The Coilless Tokamak. G. Marklin.
2D23. Ionization Effects on Tokamak Edge Turbulence. S. R. Choudhury, P. K. Kaw, and S. Rath.
2D24. Neutral Particle and Parallel Plasma Transport in Pump Limiters. L. W. Owen and P. K. Mioduszewski.
2D25. Effect of an Iron Core on Plasma Positional Stability. E. R. Solano and G. H. Neilson.
2D26. Candidate Mode for Electron Thermal Energy Transport. Y. K. Pu, B. Coppi, and S. Migliuolo.
2D27. Energy Confinement in Turbulent Fluid Plasmas. E. Hameiri and A. Bhattacharjee.
2D28. Application of an Improved Relativistic Absorption Model for Electron Cyclotron Current Drive. K. Matsuda.
2D29. Alpha Particle Induced Oscillation Bursts in Burning Tokamak Plasma and the Effects on Ash Control. V. Varadarajan and G. H. Miley.

2D30. Electron Cyclotron Emission from ECH and Ohmically Heated Tokamak Discharges. R. W. Harvey and M. R. O'Brien.
2D31. A Kinetic Model for Tearing Mode Layers in a Torus. J. W. Connor, S. C. Cowley, and R. J. Hastie.
2D32. Thermal Alpha Effect and Control for ETR-type Reactor. S. C. Hu and G. H. Miley.
2D33. Conditions for Fusion with Minimal Neutron Production. L. Sugiyama.
2D34. Relating Resistive and Adiabatic Alternating Dimension Codes. A. A. Blank and M. Kress.
2D35. Statistical Dynamics of a Two Field Model of Drift Wave Turbulence. F. Gand, P. H. Diamond, and A. E. Koniges.
2D36. Drift Wave Model Tokamak Ignition Projections with a Zero-dimensional Transport Code. R. E. Waltz, R. R. Dominguez, and F. W. Perkins.
2D37. Power Requirements of Current Drive. A. H. Boozer.

WEDNESDAY MORNING 9:00am - 1:00pm

3C POSTER SESSION
Gatlinburg, Glades, LeConte Rooms
9:00-11:00am

3C1. Analytic Approach to Error Field Perturbation Profiles in an RFP. K. L. Sidikman, J. D. Callen, and R. A. Nebel.
3C2. RF Current Drive "Efficiencies" Derived Using Klima's Relation. P. M. Bellan.
3C3. The Evolution of Resistive Ballooning Modes in the Banana-Plateau Collisionality Regime. A. K. Sundaram and J. D. Callen.
3C4. A Tearing Mode Energy Principle for an Axisymmetric Plasma. M. S. Chu, M. S. Chance, J. M. Greene, and T. H. Jensen.
3C5. The Kinetic Stabilization of Energetic Particle Internal Kink Mode and Fishbone Oscillations. Y. Z. Zhang, H. L. Berk, and S. M. Mahajan.
3C6. A Particle Method for Collisional Kinetic Equation. G. Russo.
3C7. Helical Coil Driven Sawteeth. M. Kress and K. S. Riedel.
3C8. Two-sided Equations for Quasilinear Ballooning Mode Saturation. K. S. Riedel.
3C9. Nonlinear Evolution of the m = 1 Quasi-Interchange Mode in Toroidal Geometry. F. L. Waelbroeck and R. D. Hazeltine.
3C10. Waveguide FEL Code Results for ELF and MTX. J. A. Byers and R. H. Cohen.
3C11. Electromagnetic Trapped-Particle Sideband Instability. B. I. Cohen and R. H. Cohen.
3C12. Magnetic Island Formation in Three Dimensional Plasma Equilibria. C. Hegna and A. Bhattacharjee.
3C13. Extended Neoclassical MHD Equations. Y. B. Kim and J. D. Callen.
3C14. Free Energy and Entropy Evolution in Collisional, Magnetized Plasmas and Neoclassical MHD. J. D. Callen and Y. B. Kim.
3C15. Degradation of Energy Confinement in Tokamaks due to Rotational Gyroviscous Effects. W. M. Stacey, Jr..
3C16. Adiabatic Evolution of a Kinetic FRC. R. B. Webster, J. L. Schwarzmeier, H. R. Lewis, and C. K. Choi.
3C17. Long Wavelength Collisional Ion Temperature Gradient Modes. T. M. Antonsen, Jr. and P. N. Guzdar.
3C18. Self-Similar Evolution in the Nonlinear Stage of the Undular (Ballooning) Instability. K. Shibata, T. Tajima, and R. Matsumo.
3C19. Generation of Potentials in the Mirrortron. R. F. Post.
3C20. Ignition in CIT with etta(i)-mode Transport. L. M. Hively and C. W. Bolton.
3C21. Reactor Relevant Fast Wave Current Drive Regimes in Tokamaks. V. S. Chan and S. C. Chiu.
3C22. A Basic Analytic Model for Divertor and Scrape-off in Tokamaks. A. Punjabi.
3C23. Effects of Inverted Density Profiles and Impurity Concentration Gradients on Confinement in H-Mode Discharges. P. W. Terry, H. Biglari, and P. H. Diamond.
3C24. Current Drive for a High-Beta Reactor. K. Evans, Jr. and D. A. Ehst.
3C25. MHD Simulation of Tokamak Fueling by the Injection of Compact Toroids. D. E. Shumaker, A. A. Mirin, and J. H. Hammer.

3C26. Full-Wave Calculations in Flux Coordinates for Toroidal Geometry. B. A. Carreras, V. E. Lynch, E. F. Jaeger, and D. B. Batchelor.
3C27. On the Bifurcation of Periodic Traveling Waves in the Equations of Collisionless Plasma Kinetic Theory. J. P. Holloway and J. J. Dorning.
3C28. Use of 2-D Codes for Stability Studies of 3-D Configurations. J. L. Johnson, M. Wakatani, Y. Nakamura, and K. Ichiguchi.
3C29. Theoretical Particle and Energy Flux Formulas for Tokamaks. C. E. Singer.
3C30. Ignition by Neutronless Fusion Reactions. B. Coppi, L. Sugiyama, and R. Englade.
3C31. Bootstrap Current Enhancement in Tokamaks. E. C. Crume, Jr., J. S. Tolliver, and K. C. Shaing.
3C32. Propagation of Mode-Converted Ion-Bernstein Waves in Toroidal Plasmas. A. K. Ram and A. Bers.
3C33. Kinetic Effects on the FRC Tilt. J. L. Staudenmeier, H. R. Lewis, D. C. Barnes, and J. L. Schwarzmeier.
3C34. Toroidal Electron Temperature Gradient Driven Turbulence. W. Horton, N. Bekki, B. G. Hong, T. Tajima, and W. M. Tang.
3C35. Effect of Compressibility on Resistive Interchange Mode Stability for Stellarators and Torsatrons. J. N. Leboeuf, B. A. Carreras, N. Dominguez, G. S. Lee, V. E. Lynch, and D. A. Spong.
3C36. Energetic Particle Stabilization of Kink Modes in Tokamaks/Sawtooth Stabilization by Energetic Traped Particles. C. Z. Cheng, R. B. White, P. H. Rutherford, P. Colestock, and M. N. Bussac.
3C37. The Nuclear Dynamo - Can a Nuclear Tornado Annihilate Nations?. J. R. McNally, Jr..

3D POSTER SESSION
Gatlinburg, Glades, LeConte Rooms
11:00am-1:00pm

3D1. Interaction of Energetic Ring-Current Protons with Magnetospheric Hydromagnetic Waves. A. A. Chan and R. B. White.
3D2. Ballooning Stability of a Toroidally Rotating Plasma. A. Sen and A. K. Sundaram.
3D3. Fast Solutions to the Grad-Shafranov Equations. Y. Baransky.
3D4. Variational Formulation for a Multi-Fluid Flowing Plasma with Application to the Internal Tilt Mode of a Field-Reversed Configuration. L. C. Steinhauer, A. Ishida, and H. Momota.
3D5. Quantitative Analysis of Collisionless Tearing Modes in a Modified Harris Equilibrium. N. T. Gladd.
3D6. H-Mode Simulations of DIII-D Using Drift Wave Models. R. R. Dominguez and R. E. Waltz.
3D7. A 3-D Code for Calculating Neutral Transport in Axisymmetric Plasmas. P. M. Valanju, J. C. Wiley, and D. W. Ross.
3D8. The Effects of Radial Momentum Transfer on Neutral Beam Driven Currents in Tokamaks. J. Mandrekas and W. M. Stacey, Jr..
3D9. Transport Theory of Impure Tokamak Plasma with Strong Rotation. C. T. Hsu and D. J. Sigmar.
3D10. Analytic Treatment for Mode Conversion in the ICRF Problem. H. Ye and A. N. Kaufman.
3D11. Global ICRF Wave Propagation in Edge plasma and Antenna Regions using the 2-D Finite Difference Code Orion. E. F. Jaeger, D. B. Batchelor, and H. Weitzner.
3D12. Transport Simulations of Ohmic and ECRH Experiments at TFTR, T-10 and TEXT. M. H. Redi, W. M. Tang, P. C. Efthimion, D. R. Mikkelsen, and D. R. Brower.
3D13. Evolution of Helical Magnetohydrodynamic Turbulence from a Nearly Force-free Initial State. J. P. Dahlburg, R. B. Dahlburg, and J. T. Mariska.
3D14. Analysis of Lower Hybrid RF Stabilization of Tearing Modes in the Tokamaks. X. Q. Xu and M. N. Rosenbluth.
3D15. Three-Dimesional Plasma Equilibrium Near an Internal Separatrix. A. H. Reiman, N. Pomphrey, and A. H. Boozer.
3D16. Stability of the "Peapod" Shaped Tokamak Against Low-n MHD Modes. S. P. Hakkarainen and J. P. Freidberg.
3D17. Hot-particle Effects on High-n Instabilities in Tokamaks. G. Rewoldt.
3D18. Computer Simulation of Transport Driven Current in Tokamaks. W. J. Nunan, R. D. Sydora, and J. M. Dawson.

3D19. Interaction of a Neutral Beam and an Ambient Plasma. F. Kazeminejad, R. Bingham, J. M. Dawson, J. N. Leboeuf, and R. D. Sydora.
3D2Ø. RF Tokamak Plasma Confinement Due to Brillouin Scattering off Trapped Particle Modes in Lower Hybrid Frequency Range. V. Stefan, A. R. Wilson, and E. Salberta.
3D21. Ideal Stability of Axisymmetric Toroidal Plasmas with Sheared Equilibrium Flows. J. Milovich and A. Bhattacharjee.
3D22. Parametric Quasi-Mode Decay at Lower Hybrid Geometric Foci. I. Park and J.-M. Wersinger.
3D23. Cross-Field Sheath in a Magnetized Plasma. D. Holland, B. D. Fried, and G. J. Morales.
3D24. Impurity Transport in a Rotating Tokamak Plasma. K. L. Wong and C. Z. Cheng.
3D25. Mode Conversion and Absorption of Lower Hybrid Waves in In-homogeneous Magnetic Fields. S. Cho and D. G. Swanson.
3D26. Generating Functions and Toroidal Magnetic Fields. E. R. Tracy and A. H. Boozer.
3D27. Alpha Particle Induced Fishbone Oscillations. F. Porcelli, B. Coppi, and S. Migliuolo.
3D28. Magnetic Helicity Injection for Configurations with Field Errors. J. M. Finn and T. M. Antonsen, Jr..
3D29. Neoclassical Quasilinear Transport Theory of Fluctuations and its Applications. K. C. Shaing, W. A. Houlberg, and E. C. Crume, Jr..
3D3Ø. Nonlinear Gyrokinetic Maxwell-Vlasov Equations Using Magnetic Coordinates. A. Brizard, R. B. White, and T. S. Hahm.
3D31. Second Harmonic ECH Plasma Breakdown - A Comparison of Theory with Initial Experiments in ATF. M. D. Carter, D. B. Batchelor, G. L. Bell, T. S. Bigelow, E. C. Crume, Jr., J. C. Glowienka, R. C. Goldfinger, J. H. Harris, D. L. Hillis, S. Hiroe, L. D. Horton, H. C. Howe, R. C. Isler, M. M. Menon, M. Murakami, G. H. Neilson, D. A. Rasmussen, T. L. White, and J. B. Wilgen.
3D32. Magnetic Tearing of Plasma Discharges due to Nonuniform Resistivity. A. B. Hassam.
3D33. Dissipative Trapped Particle Modes in Tandem Mirrors. C. Y. Chen and H. L. Berk.
3D34. The Effect of Compressibility on Linear and Nonlinear Resistive MHD Toroidal Calculations. V. E. Lynch, L. A. Charlton, B. A. Carreras, and J. A. Holmes.
3D35. An Improved Method for Calculating Boozer Coordinates in Stellarators. J. A. Rome.
3D36. Wall Reflection Model for the Rays Code. R. C. Goldfinger and D. B. Batchelor.
3D37. Heating and Fuelling Effects in Simulations of a Density Limit in Radiation-Dominated Tokamak Discharges. D. P. Stotler and G. Bateman.

NEOCLASSICAL MHD EFFECTS ON PRESSURE-GRADIENT DRIVEN AND TEARING INSTABILITIES*

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And

J. D. Callen
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Madison, Wisconsin

It has been demonstrated that pressure-gradient driven and tearing instabilities can be significantly modified in the banana-plateau collisionality regime $[\mu_e/\nu_e \sim \sqrt{\varepsilon}/(1+\nu_{*e}) > \varepsilon^2]$ by including the proper neoclassical flows, currents, and viscous effects. The new feature of our work is to carefully examine the transition from the resistive Pfirsch-Schulüter regime to the neoclassical long-mean free path regime (where the fluctuating bootstrap current in Ohm's law dominates over the conventional instability drives). Our results demonstrate both the smooth connection between resistive and neoclassical MHD instabilities as well as contrasting their differences. The neoclassical instability is generally more robust, being characterized by a larger radial mode width and a higher growth rate. It also persists in the absence of the usual magnetic field-curvature drive and is only very weakly stabilized by compressibility. Scalings with respect to β, n (toroidal mode number) and μ (neoclassical viscosity) are examined using a large aspect ratio, 3-dimensional initial value code which solves linearized equations for the magnetic flux, fluid vorticity, density and parallel ion flow velocity in axisymmetric toroidal geometry. These results are then compared with analytic calculations. Also, work is in progress on a cylindrical nonlinear code to study neoclassical effects on the evolution of low mode number tearing instabilities.

* Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

STREAMER FORMATION IN PLASMA WITH A TEMPERATURE GRADIENTS*

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College Park, MD 20742

A plasma with a temperature gradient can be unstable to a negative compressibility mode, the η_e mode,[1] in the wavelength regime $k > \omega_{pe}/c$. This instability exists in both collisional and collisionless plasma. A simple set of equations have been derived which describe the nonlinear behavior of the instability. These equations have been integrated using a 2-D pseudo-spectral code. The turbulent 2-D fluctuations exhibit a spontaneous transition to a state of enhanced transport in which highly elongated vortices (streamers) enable the fluid to take large steps along the temperature gradient. In this quasi-one-dimensional state the thermal transport greatly exceeds that given from the simple expression $D_\perp \sim \gamma/k_\perp^2$. A simple analytic calculation has been completed which demonstrates that the collapse from a 2-D state to a 1-D state is favored. In the collisional regime the anomalous transport scales as $D_\perp \sim D_r \sim \eta_\parallel c^2/4\pi$, the classical flux diffusion rate.

*Supported by the U.S. Department of Energy.

1. Y. C. Lee, J. Q. Dong, P. N. Guzdar, and C. S. Liu, Phys. Fluids 30, 1331 (1987).

Dynamics and Fluctuation Spectrum of Ion Temperature Gradient Driven Instabilities in a Sheared Magnetic Field with Multiple Rational Surfaces*

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Department of Physics, UCLA, Los Angeles, CA 90024

Ion temperature gradient driven (η_i) instabilities in a sheared slab with multiple rational surfaces have been studied using a newly developed three dimensional gyrokinetic particle simulation model. In order to facilitate the calculation, the electron response is assumed to be adiabatic and a multiple spatial scale expansion technique is also used,[1] which enables us to "freeze in time" the background inhomogeneities. From these simulations, we can then determine the steady-state fluctuation amplitude for the electrostatic potential, the ion current density and the ion pressure as well as the corresponding steady-state particle and heat fluxes. The simulation has been carried out for the relevant regime in which kinetic ion effects are important and for which ion Landau damping serves to localize the fluctuations to the mode rational surfaces. One important feature from the 3D simulation is that the fluctuation spectrum for the potential decreases rapidly for large poloidal wavenumbers, whereas the fluctuation spectrum for the ion pressure remains relatively constant. This is in rough agreement with an estimate based on the renormalized mode coupling theory for the regime where a significant real frequency exists for the fluctuations.[2] The particle simulation results also indicate that the ion thermal flux is nonvanishing in the steady state for a collisionless plasma, although its value is somewhat lower than the quasilinear level which occurs at the onset of saturation. Furthermore, there exists a significant ion perpendicular heat flux which is the result of the E×B convection for the particles with different particle velocities. As expected, the measured real frequency and mode structure at each rational surface are closely related to those of the n=0 radial eigenmode. The comparison of the 3D results with those from the 2D (single rational surface) simulation[3] as well as the scalings with respect to shear, density and temperature scale lengths, and electron dissipative effects will be presented.

*This work is supported by DoE Contract #DE-FG03-86ER53225.

+Princeton Plasma Physics Laboratory, Princeton , New Jersey 08543

[1]W. W. Lee, JCP 72, 243 (1987).
[2]T. S. Hahm, W. W. Lee and R. D. Sydora, this conference.
[3]W. W. Lee and T. S. Hahm, Bull. Am, Phys. Soc. 32, 1889 (1987).

Rising-Bucket Current Drive*

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Intense, pulsed microwave sources such as free-electron lasers offer the potential for novel current-drive scenarios in tokamaks. One such scheme is rising-bucket current drive, which operates on electrons trapped in the nonlinear phase-space islands set up by the wave. The islands (buckets) and the electrons trapped therein can be accelerated by adiabatically varying $N_{\|}$ (by, for example, reflecting the microwave beam off a cylindrical mirror) along a field line; variation of the cyclotron frequency can also be exploited.

Analytic and orbit-code studies have produced the following conclusions: Electrons with energies up to 100 keV can be obtained with electron temperatures in the few keV range as in MTX, while energies in excess of 200 keV can be obtained for ITER parameters. Adiabaticity requirements can be satisfied for realistic field strengths and scale lengths. The process leads to opacities and current-drive efficiencies η which can significantly exceed their quasilinear counterparts. By exploiting the adiabaticity requirement, good harmonic selectivity can be obtained, thereby overcoming the harmonic-competition problem present for quasilinear ECRH at reactor temperatures[1]. For ITER with 10 GW FEL pulses, good harmonic selectivity can be obtained using third-harmonic extraordinary mode. High maximum $N_{\|}$'s, about 0.9, are required for appreciable enhancement of η over the single-harmonic quasilinear value [yielding $n(10^{20}\ \mathrm{m}^{-3})I(\mathrm{A})R(\mathrm{m})/P(\mathrm{W}) \sim 0.4$ in ITER], but lower values suffice to merely exploit the adiabatic harmonic selection. Ray-tracing studies indicate that propagation into the plasma is not problematic.

Outstanding issues include microstability of the resultant distribution function and self-consistent penetration of different parts of the beam. We have begun to address these issues with the particle code ZOHAR[2]; preliminary results will be presented.

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

[1] G. R. Smith, R. H. Cohen, and T. K. Mau, Phys. Fluids **30**, 3633 (1987)

[2] A. B. Langdon and B. F. Lasinski, Methods Comput. Phys. **16**, 327 (1976)

1988 Sherwood Theory Conference
April 18 - 20, 1988
Gatlinburg, Tennessee
Annual Controlled Fusion Theory Conference

Quasi-helically Symmetric Toroidal Stellarators

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IPP-EURATOM Association
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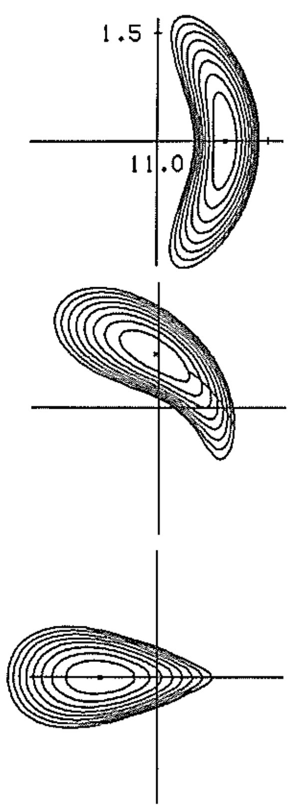
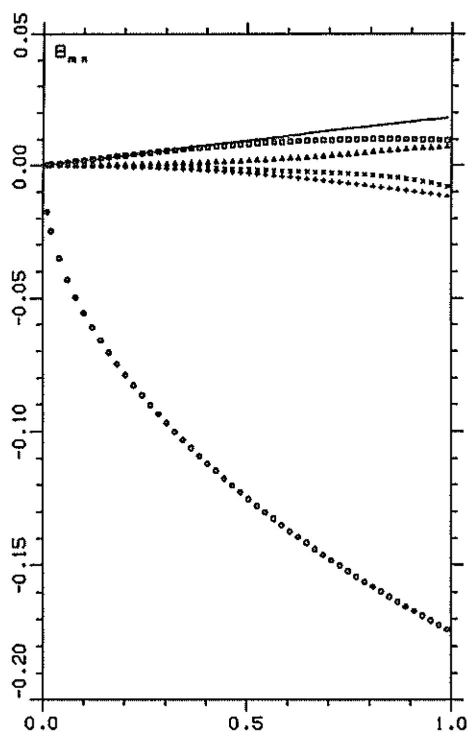
It is computationally shown that there are toroidal stellarators whose magnetic field strength is helically symmetric in magnetic coordinates. Accordingly, these stellarators, without collisions, strictly confine guiding centre orbits. The left figure shows flux surface cross-sections of a quasi-helically symmetric stellarator with $\beta = 0$, aspect ratio $A \approx 11$, and 6 periods; its magnetic well is approximately marginal; the rotational transform is characterized by $\iota(0) \approx 1.4$, $\iota(1) \approx 1.5$. The right figure shows dominant Fourier coefficients of the magnetic field strength analyzed in magnetic coordinates versus normalized flux label s; $-[B_{0,0} - B_{0,0}(s=0)]$, $\bigcirc B_{1,-1}$, $\square B_{2,-2}$, $\triangle B_{4,-3}$, $\times B_{5,-4}$, $+B_{3,-2}$. In this computational realization coefficients disturbing the quasi-symmetry are $\approx 10^{-3}$ at half the plasma radius and $\approx 10^{-2}$ at the plasma boundary. Consequences of the existence of quasi-helically symmetric stellarators will be discussed.





1988 Sherwood Theory Conference
April 18 - 20, 1988
Gatlinburg, Tennessee
Annual Controlled Fusion Theory Conference

Neoclassical Transport Calculations for Helias and Quasi-helically Symmetric Stellarators

W. Lotz, J. Nührenberg
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IPP-EURATOM Association
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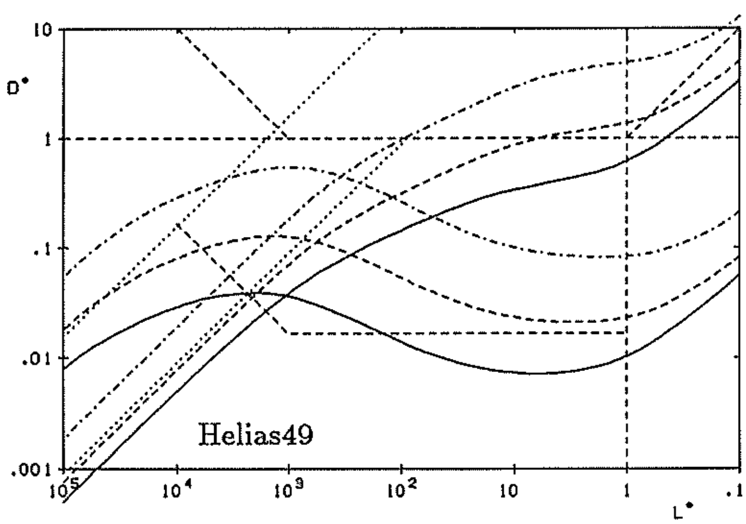
Monte Carlo simulations with monoenergetic particles yield neoclassical transport coefficients in stellarators of general geometry over wide ranges of mean free paths, ratios of plasma- to gyroradius, and radial electric fields. After normalization of such results to the plateau value ($D^* = 1$) and to half the connection length ($L^* = 1$) they can be represented by simple formulas involving dimensionless quantities as the aspect ratio, the ratio of plasma- to gyroradius, and the ratio of particle energy to electric potential. These formulas can be used to obtain results for a Maxwellian energy distribution by convolution. These Maxwellian results are compared with theory and with simulations using a particle distribution subjected to pitch angle as well as energy scattering. Good agreement is found. Particle as well as energy transport coefficients are obtained for ions and electrons; zero-dimensional estimates of particle and energy confinement times are also obtained.

The computational procedure outlined above leads to results of the type shown in the Figure which will be discussed in detail. Applications to Helias and quasi-helically symmetric stellarators will be presented.



MINIMUM-DISSIPATION STATES AND THE RFP

David Montgomery* and Lee Phillips, Dartmouth College

The "minimum rate of energy dissipation" is a variational principle with a solid history in hydrodynamics. Here, we attempt its generalization to incompressible MHD with constant transport coefficients. It is explored for the case of a column of magnetofluid subject to magnetic fields and electric fields applied in the axial (z) direction. The energy dissipation rate is minimized subject to the constraints of fixed time-averaged rate of supply (and dissipation) of magnetic helicity, and constant axial magnetic flux. The Euler-Lagrange equation for the time-averaged current density $\mathbf{j}$ is

$$\nabla \times \mathbf{j} + \alpha \mathbf{j} + \nabla s = 0$$

Here, α is a Lagrange multiplier and s is a solution of Laplace's equation whose gradient is periodic in z. Periodic boundary conditions in z are assumed, and magnetic boundary conditions are $\mathbf{B} \cdot \hat{e}_r = 0$ at $r = a$, with the boundary a circular cylinder. If no boundary conditions on $\mathbf{j}$ are imposed, s may be set equal to zero, and the implications of the theory seem to be identical to those of Taylor's "minimum energy" principle. If perfectly-conducting boundary conditions are imposed on both $\mathbf{j}$ and $\mathbf{B}$, the implications are rather different. For low enough values of the applied electric field, the predicted state is an axisymmetric one with a force-free core ($\mathbf{j} \parallel \mathbf{B}$) surrounded by a layer with $\mathbf{j} \times \mathbf{B} \neq 0$, and the ratio j/B strongly dependent upon r. A conventional "$F - \Theta$" dependence may be calculated explicitly, and is $F \cong 1 - 0.52\Theta$, with the "window" of reversed-field operation being approximately $1.9 < \Theta < 2.75$. (Above $\Theta > 2.75$, the axisymmetric state ceases to be the state of minimum dissipation, and the whole theory breaks down.) $B_z(r)$ and $j_z(r)$ are both Bessel functions plus constants. $j_z(r)$ does not reverse when $B_z(r)$ does, but goes smoothly to zero as $r \longrightarrow a$. $(\mathbf{j} \times \mathbf{B}) \cdot \hat{e}_r$ is only radially inward for all $r < a$ when $F < 0$, implying a virtue to "field reversal" that is unconnected with stability. Several of the predicted features are qualitatively similar to the recent computational results of Dahlburg et al. The $F - \Theta$ graph lies about as far above the experimentally-measured points for laboratory RFP's as the Taylor curve lies below them. It seems likely that the region between the two curves is accessible to more exotic boundary conditions on $\mathbf{j}$.

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The Liouville Equation and The Study of Two-dimensional MHD Equilibria

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The Liouville equation: $\nabla^2\phi = \frac{\lambda^2}{16} e^{-\phi}$ arises as a model equation describing two-dimensional MHD equilibria (ϕ is a flux function for the magnetic field) and is of particular interest in plasma physics as it supports the well known *island chain* solution.[1]

Direct application of the *inverse scattering transformation* (IST) has failed to provide useful solutions, because of an incompleteness in the scattering data. Here we discuss[2,3] how to construct, in principle, more general solutions with periodic boundary conditions based on a modified IST method and the work of A.C.Ting et al.[4] This approach hold promise of generating a large class of "higher order" island chain solutions, with both periodic and perhaps quasi-periodic islands. The ultimate aim of this work is to perform a global stability analysis on these solutions and deduce analytically the lowest energy equilibrium with nontrivial topology. Progress towards this goal will be reported.

References:

1) J. M. Finn and P. K. Kaw, Phys. Fluids 20, 1, 72-78 (1977).
2) E. R. Tracy, C. H. Chin and H. H. Chen, Physica 23D (1986) 91-101.
3) E. R. Tracy, A. J. Neil, H. H. Chen and C. H. Chin, Proceedings of the Conference on Nonlinear Evolution Equations, Solitons and the Inverse Scattering Transformation. Oberwolfach, West Germany July 27 - August 2 1986.
4) A. C. Ting, H. H. Chen and Y. C. Lee, Phys. Rev. Lett. 53 (1984) 1348.

1988 SHERWOOD THEORY CONFERENCE
GATLINBURG, TENNESSEE

A MODEL OF INTERMITTENT TURBULENCE IN COMPRESSIBLE SELF-GRAVITATING GAS AND VLASOV PLASMA

P. H. Diamond and H. Biglari

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A simple physical model which describes the dynamics of turbulence and the spectrum of density fluctuations in compressible self-gravitating gas and Vlasov plasma is presented. Since each system tends to self-organize into structures via the mechanism of Jean's collapse (into density 'clouds' for the gas and phase space density 'holes' for the plasma), a natural way to describe the turbulence in such systems is in terms of a virialized cascade. In such a cascade, density and velocity fluctuations are related by the the condition of marginality to Jeans instability. It is then possible to construct simplified cascade models which describe the spectrum of velocity and density fluctuations for the gas, and phase space density fluctuations for the plasma. Intermittency is then straightforwardly introduced by allowing for the possibility of turbulence with fractal dimensionality.[1] Several features of Vlasov plasma turbulence computer simulations[2] can then be explained using the model developed.

[1] U. Frisch et al., *J. Fluid Mech.* **87** (1978).
[2] R. H. Berman et al., *Phys. Fluids* **29** (1983).

SELF-SIMILAR, OHMIC RAMP DOWN OF RFP EQUILIBRIA

E. J. Caramana, R. A. Nebel, J. A. Phillips, D. A. Baker,
R. F. Gribble, and C. P. Munson

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Time and space separable Ohmic solutions of the 1-D transport equations have been found that apply to the ramp-down phase of an RFP discharge. These solutions allow the magnitude of the profiles of $B_\theta(r)$ and $B_\phi(r)$ to decay but maintain the profile shapes, including the reversal of the toroidal field at the wall. For particular ramp-down rates and resistivity profiles, we have found solutions that are stable (and maintain that stability) to all current driven MHD modes. Thus, we have a possible prescription of how to produce RFP discharges that do not require the dynamo effect during the termination phase.

We have tried this prescription experimentally on ZT-40M with the following results. First of all, ramp down rates of the current close to the theoretical prediction of that which is necessary can be achieved, although we are unable to program the toroidal field to precisely match the theoretical parameters. Also, a significant reduction in the fluctuation level of the toroidal flux is observed in ZT-40M during the ramp down. One-Dimensional transport simulations of the experiment data will be presented.

The importance of these results is threefold. First of all, slow rampdown is needed for the next generation of RFPs to protect the walls from damage caused by fast terminations. Stable rampdown should be an optimal way to do this. Secondly, if these discharges do shut off the dynamo effect, we have an opportunity to experimentally study transport in its absence. Comparison of these discharges with constant current discharges may enable us to experimentally determine how significant the dynamo contribution to transport is. Finally, since the required ramp-down rates become smaller at high temperatures, one may want to operate a reactor in a ramp-down regime to improve confinement.

Electron Cyclotron Heating and Current Drive in ITER*

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For the International Thermonuclear Experimental Reactor (ITER), we are considering the utilization of electron-cyclotron (EC) power as an alternative to other heating and current-drive systems. Possible applications of EC power are listed below together with some of the issues that we are studying.

- Initial gas breakdown and heating by EC power would eliminate the need for a large inductive voltage for breakdown and thereby allow use of a thicker conducting wall that could better withstand disruptions, stabilize low-frequency modes, and confine tritium. We find that 30 MW of EC power could ionize and heat gas in ITER to ~ 0.5 keV at a density of $2 \times 10^{19}\,\mathrm{m}^{-3}$.

- We are defining the role that can be played by powerful (30 MW) EC power in conjunction with Ohmic power during ramp up of the current. Particular attention is paid to ramp up from 0 to 1 MA, to which EC current drive can contribute even for efficiency < 0.03 Amps/Watt. At 1 MA, current drive with 1–2 MeV neutral beams becomes possible.

- The option of a high-temperature, low-density plasma in ITER suggests that a current profile favorable for MHD equilibrium and stability might be supported partially by EC power. We are studying the difficulty of achieving this goal because of overlap of cyclotron harmonics at high T_e.[1]

- Major disruptions might be controlled to some extent by suppression of tearing modes by means of EC heating or current drive. The primary issue is whether the power or current can be localized with sufficient precision.

We are considering the suitability of both steady (gyrotron) and pulsed (free-electron laser) power for these applications.[2]

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† Supported by USDoE under Contr. DE-FG02-84-ER5-3187.

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2 Other papers at this meeting on current-drive schemes that rely on an intense (FEL) source are those by R. H. Cohen, T. D. Rognlien, G. R. Smith, and B. I. Cohen and by T. D. Rognlien, R. H. Cohen, and W. M. Nevins.

NONLINEAR MECHANISMS FOR DRIFT WAVE SATURATION AND INDUCED PARTICLE TRANSPORT*

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and
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Previous studies of drift instabilities in a shear-free slab using gyrokinetic particle simulation have shown that systems dominated by a few low-k modes with $\Delta\omega/\omega \lesssim 1$ have (1) an intrinsically ambipolar steady state particle flux, (2) an increase in guiding center density for both species near the maxima of the electrostatic potential, and (3) a net phase velocity of the saturated drift waves directed down the density gradient which, along with the saturation level, are enhanced by the electron pitch angle scattering‡. Here, we explain the collisionality dependences. The saturation levels are set by a balance between the nonlinearly generated electron and ion fluxes. Depending on the parameter regime, the ion flux is due either to weak nonresonant ion $\vec{E} \times \vec{B}$ diffusion or to the coherent advection of high density regions. The electron flux is driven by the $\vec{E} \times \vec{B}$ diffusion of near-resonant electrons. In the 2 $\frac{1}{2}$-dimensional geometry, the resonant electron population is decreased because the resonant electrons are selectively accelerated out of the resonant interval. The collisionality dependences arise because the collisions repopulate the resonant interval. In the fully three-dimensional geometry, there are multiple resonances and a possibility of resonance overlap for the electrons. The effects of these will be considered.

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SUPPRESSION OF SAWTOOTH OSCILLATIONS IN PLASMAS WITH HIGH ENERGY PARTICLE POPULATIONS*

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Recent experiments at the JET facility[1] have shown that ion cyclotron resonance heating (ICRH) can suppress sawtooth oscillations for as long as the RF power is applied (~3 sec.), while a sawtooth crash ("monster sawteeth") takes place shortly after ICRH has been switched off. We argue that sawtooth suppression during ICRH is due to the stabilization of the relevant $n^{o}=1$, $m^{o} \simeq 1$ global internal modes by the high energy ($\varepsilon_h \sim 100$ keV), magnetically trapped ions produced by the RF fields. In particular, we show that, while the mode growth rate and the contribution to it by the electron population are weakened by the higher temperature produced by the injected RF power, the energetic ions tend to: i) add a significant negative contribution to the bulk plasma ideal MHD stability parameter λ_H (λ_H is proportional to the negative of the potential energy functional δW_{MHD}); ii) provide a viscous-like dissipative term arising from a mode-particle resonance $\omega = \omega_{Dh}^{(o)}$, where $\omega_{Dh}^{(o)}$ is the bounce averaged magnetic drift frequency of a magnetically trapped high energy ion. We show that i) and finite ion Larmor radius effects render the relevant ideal modes marginally stable, while the mechanism in ii) is responsible for the stabilization of resistive modes.

We point out that the philosophy we have constantly adopted for the interpretation of the JET experiments is that i) the magnetic helicity parameter $\iota(\psi) = 1/q(\psi)$ falls below unity on the magnetic axis and that the magnetic shear on the surface where $\iota(\psi) = 1$ does not become vanishingly small, ii) the ideal MHD theory is inadequate for the relevant plasma regimes.

*Sponsored in part by the U.S. Department of Energy
+Culham Laboratory, Abingdon, England
#JET Joint Undertaking, U.K.

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Nonlinear Consequences of $m = 1$ Evolution in Toroidal Geometry

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We study numerically two situations involving the nonlinear evolution of the $m = 1$ mode in toroidal geometry. In the first we study the linear stability of the saturated internal kink instability with respect to high n modes. This is carried out for several cases for modes in the range $n = 6 \rightarrow 15$ against a saturated internal kink plasma represented by $n \leq 5$. In contrast with the analytic calculation of Bussac and Pellat,[1] we have not yet found unstable high n modes in these saturated kink plasmas. The second situation we examine is the nonlinear interaction of the resistive $m = 1$ mode with resonant modes having $m/n < 1$ for safety factor profiles having $q_0 < 1$. The relevance of this topic is suggested by the observation of $q_0 < 1$ on several experiments, even after sawtooth events. We consider safety factor profiles with q_0 in the range 0.6-0.75 and focus on the development and interaction of the 2/3, 3/4, 4/5, and 1/1 helicities. Initial results show the growth of islands associated with these instabilities. Rutherford has suggested[2] that the nonlinear interaction of modes having $m/n \leq 1$ may be responsible for this behavior.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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Nonlinear Density and Potential Modifications Induced in the Edge Plasma by High Power ICRF Antennas — II. Collisional Theory*

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This paper extends the study[1] of the nonlinear interaction of ICRF with the edge plasma into the collisional regime. The goal is to develop a theory of the edge plasma, including relevant ICRF interactions, which can determine n, Φ, and T self-consistently. These quantities both affect and are affected by the transport of bulk plasma and impurities and the coupling of waves into the interior.

For an edge temperature of about 25 eV (near the antenna) the Coulomb mean free path scales as $\lambda \sim 6 \times 10^{14}/n$ (cgs units), hence λ can easily be comparable to the relevant scale lengths in the toroidal direction, viz. the length of the antenna and the distance of an observation point from the antenna.

The kinetic theory developed for the collisionless regime[1] is extended here to include Coulomb collisions to order ν/ω allowing ν and $v \cdot \nabla$ to be comparable. The resulting kinetic equation for f on the slow time scale contains a nonlinear collisional term which describes both collisional heating and an accompanying parallel force which expels electrons from the interaction region near the antenna. Employing a model collision operator which may be inverted by a velocity Fourier transform technique,[2] the kinetic equation is solved for the density and potential variations along the field line. In general, the resulting electrostatic potential $\Phi(z)$ is of the order of the collisionless ponderomotive potential $\psi(z')$, but the interaction is nonlocal, i.e. $z-z'$ can be several mean free paths. Nonetheless, in the collisionless limit $\lambda \to \infty$ the local result[1] $\Phi(z) \propto \psi(z)$ is recovered. Limiting cases will be discussed and applied to situations of interest for IBW and fast wave heating.

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Nonlinear Density and Potential Modifications Induced in the Edge Plasma by High Power ICRF Antennas -- I. Collisionless Theory*

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In addition to bulk plasma heating, high-power ICRF antennas can strongly modify the edge plasma properties. The resulting changes in density, temperature, potential, and impurity concentration can influence the global particle and energy confinement. For example, in recent ion Bernstein wave (IBW) heating experiments[1,2] an rf-induced electrostatic potential and a factor of 3 increase in the particle confinement time were observed. The changes in edge parameters also strongly influence the antenna-plasma coupling and thus the heating efficiency. For these reasons, a better theoretical understanding is needed of the highly nonlinear interaction between an ICRF antenna and the plasma edge. Here, we describe a kinetic theory of the linear and nonlinear plasma response to an electromagnetic rf wave of arbitrary polarization, retaining the spatial variation of the rf field along and across the equilibrium magnetic field. An expansion in Ψ/T = (ponderomotive potential/temperature) is carried out, and the treatment is restricted to the nonresonant regime ($\omega > k_{\|} v_{\|}$) relevant to the edge plasma. The present paper describes the collisionless limit and a companion paper[3] describes collisional modifications. The density depression due to the ponderomotive force along a field line is calculated for each species, and it is shown that an ambipolar potential Φ (of order the ponderomotive potential) results from the requirement of quasineutrality. The size of Ψ_i/Ψ_e, and hence the sign of Φ, is found to be sensitive to details of the rf field polarization and the $k_{\|}$ spectrum. Application of the theory to near fields typical of IBW and fast wave antennas will be discussed.

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Comparison of Particle Orbits in Both Boozer Coordinates and Real Space Coordinates*

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Detailed comparisons of particle orbits in both Boozer flux coordinates[1] and real space coordinates[2] have been made; for some types of trapped particles it has been noticed that the orbit precession in flux coordinates is slower than in real space coordinates, although a similar path is mapped out. Even severe truncation of the Boozer harmonic set does not modify this behavior – it seems to be subtle property of using flux coordinates in non-axisymmetric systems. Tokamak orbits were identical in both spaces as were circulating particles for the stellarator case. Numerical reconstruction of the vector vacuum magnetic field has been performed as a consistency check along with a thorough examination of $|b|$, the Boozer jacobian, and $\iota = \vec{B} \cdot \nabla\theta / \vec{B} \cdot \nabla\phi$. Also a re-examination of the Boozer coordinate conversion technique was evaluated. Thus far the orbit discrepancy has not been resolved.

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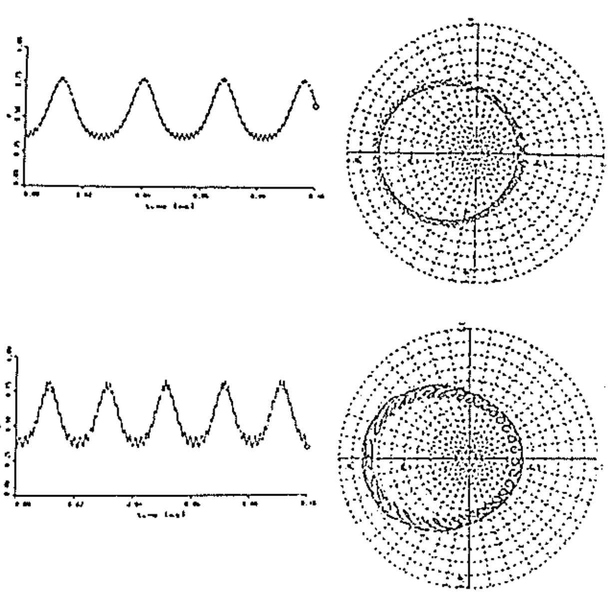

Ballooning Modes in Low Shear Tokamaks*

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Low n ballooning modes occurring in weak shear regions of tokamaks are investigated numerically. It has been pointed out by Hastie and Taylor[1] that in weak shear the growth rate becomes an oscillatory function of 1/n rather than a decreasing function of 1/n as standard ballooning theory suggests. Studies by Manickam, Pomphrey and Todd[2] with the PEST code have subsequently verified this oscillatory nature of the growth rate in low shear, centrally peaked pressure plasmas. These modes, euphemistically referred to as "infernal modes", may be unstable even when codes based on standard ballooning theory predict stability. Such modes could be important in CIT which, because of its high current, will likely have a large low shear region. They could also be important in second region experiments such as the proposed SRX or VMOD devices that rely on q-programming to reach the second region. In these devices the second stable region is reached by raising q on axis, consequently lowering shear. A numerical study is presented of this weak shear ballooning mode theory. Comparison's are made between this formulation and results of PEST calculations.

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UPPER AND LOWER BOUNDS FOR TRANSPORT COEFFICIENTS IN 3-D TOROIDAL SYSTEMS*

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Previous calculations of neoclassical transport coefficients for complex 3-D configurations have consisted of Monte Carlo guiding center simulations, numerical solutions of the linearized drift kinetic equation, and analytic calculations. In principle, the former two methods are capable of yielding accurate results in the limit of a large sample space of particles and basis functions, respectively. In practice, the sample space is limited by numerical considerations, even as an analytic calculation is limited by the approximation needed to make it tractable. It thus becomes necessary to determine the effect of this truncation/approximation, a task which heretofore has not been performed.

We develop a variational principle, appropriate for the linearized drift kinetic — Fokker Planck equation, from which both upper and lower bounds for the transport coefficients may be calculated. The bounds converge monotonically as the dimensions of the sample space increase. This property can be used to focus calculations on those portions of phase space which contribute dominantly to the transport processes. A computer code based on this principle has been developed, using Fourier/Legendre representations for the poloidal, toroidal and pitch angles. As an example, this code is used to calculate transport coefficients for an ATF plasma in the low collision frequency regime.

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SHERWOOD THEORY MEETING 1988

Non-stability of Low q Profile in Tokamaks at Zero Beta*

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We examine the stability of a low q profile ($q_0 = .7$) in tokamaks using our reduced MHD code. The low β reduced equations incorporated in the code are expanded to an order which includes the effects of toroidicity. However, the results presented here are at zero β (no pressure force). We find that down to a resistivity of $\eta = 2.5 \times 10^{-7}$, full reconnection occurs leaving the entire plasma with $q > 1$.

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

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Stabilization of Ballooning Modes by Flow*

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For several years there has been doubt whether ballooning modes (with toroidal mode number $n \rightarrow \infty$) exist in the presence of toroidal flow with shear[1]. We have now shown analytically that they do exist. Interestingly, the equation describing them contains time explicitly and thus their stability cannot be determined merely by investigating solutions with $\exp(i\omega t)$ dependence. Nevertheless, asymptotic methods can answer the stability question quite readily.

For intermediate time, on the order of a few ballooning growth times, we derive a stability criterion which enables stabilization if the rotation increases sufficiently rapidly from the center of the plasma to the outer flux surfaces. Here, the dynamic pressure acts to enhance the kinetic pressure in such a way that the gradient of the total press makes the plasma ballooning stable. For much longer time the mode is always stabilized by the rotational shear. A detailed investigation is necessary in order to see if the flow shear does not introduce other instabilities which might undo the beneficial effects on the ballooning modes. Earlier work[2] suggests that an optimistic conclusion is possible. The introduction of flow may thus offer a way to reach the second stability regime in tokamaks.

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SHERWOOD THEORY MEETING 1988

Tokamak Collisional Transport Theory Near the Separatrix

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The collisional transport theory for a tokamak plasma has been widely studied in the case of closed magnetic field surfaces. The theory is asymptotic in the small parameters ν/Ω and r_L/r_∇ (where ν, Ω, r_L and r_∇ denote collision frequency, gyrofrequency, gyroradius and typical scale length of the radial gradients, respectively) and assumes the safety factor q to be of the order of 1. Hence, in the actual cases the theory holds in the inner part of the plasma ring and the question is how far its validity can be extended towards the wall. In the case of a limiter-bounded tokamak plasma, the theory applies in principle up to the magnetic surface that is tangent to the limiter. In a tokamak with (axisymmetric) divertor, the theory fails before reaching the separatrix because q tends to become infinite there.

In the present paper, the problems connected with the extension of the collisional transport theory to the separatrix region (from the closed-magnetic-surfaces side) are considered. The (clean) plasma is assumed to be there in the Pfirsch-Schlüter regime (i.e.$\nu > \nu_b$, where ν_b is the frequency related to the poloidal motion of the particles) so that the usual two-fluid description applies. Numerical results for the ion heat flux in the case of a single-null, divertor geometry relative to different models for the poloidal dependence of the poloidal magnetic field near the separatrix will be presented. They show that the diamagnetic heat flux which is responsible for the Pfirsch-Schlüter enhancement of the cross-magnetic-surface heat flux tends to concentrate in the X-point region and its average (over the magnetic surface) value tends to increase.

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SHERWOOD THEORY MEETING 1988

Study of Pressure Gradient Modes in Finite β Plasmas *

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In the previous work[1] it was shown that when ion temperature gradient is finite, the ideal kinetic theory plasma gives rise to instability below the ideal critical β of MHD theory. For the temperature gradient $\eta_i > 2/3$ and inverse aspect ratio $\epsilon_{T_i} < 0.35$ also makes the toroidal η_i mode unstable. Larger $\epsilon_{T_i} = r_{T_i}/R$ plasmas are stable due to compressibility.In the present study we solved two coupled second order differential equations which govern the pressure gradient modes in finite β tokamak. With the full ion kinetic integral which includes the complete gyroradius effects and the ion magnetic resonances, we study $\gamma_k(\epsilon_n,\ q^2\beta,\ \eta_i,\ s,\ q,\ \tau)$ of the toroidal η_i mode and the MHD ballooning mode. The finite β stabilization of the η_i mode and the effects of parallel ion dynamics are discussed. We compare our results with a simple local dispersion relation and the previous works which neglect the parallel ion dynamics and used the fluid theory or a simpler kinetic theory.

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Ballooning Stability Environment in Arbitrary Tokamak Equilibria

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The perturbative equilibrium theory of Greene and Chance [1,2] can be imbedded in arbitrary tokamak equilibria and is therefore a powerful tool for studying the dependence of ballooning mode stability upon realistic plasma parameters. A numerical code, CAMINO, being developed from this theory, can locate a given, specified equilibrium within its own stability environment. The latter lies within a 3-dimensional space in (p_ψ, q_ψ, ψ) and depends on other parameters such as safety factor, plasma cross-section, aspect ratio, etc. The method is, in fact, the natural generalization of the S-α diagram [3] to include the effects of these parameters. The analysis includes the Mercier criterion and the effect of the finite eikonal-like parameter, θ_k. As an example, it is now possible to study vertically asymmetric equilibria and hence the theory can be applied to simulations of the recent DIII–D high β_p shots [4], showing the status of these shots in relation to the second region of stability. A description of the theory and the code will be presented together with these and other applications.

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PROFILE CONSISTENCY, HEAT PULSE PROPAGATION, AND NONLINEAR THERMAL TRANSPORT*

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It is often observed that steady state electron temperature profiles in tokamak discharges assume a canonical shape which can be related to that of a macroscopically stable and relaxed current density profile outside the region of sawtooth activity, relatively independent of the spatial deposition of any auxiliary power that may be applied. In addition, the propagation of heat pulses associated with sawtooth crashes or transient bursts of spatially localized microwave power appears to take place on a time scale considerably shorter than the steady state thermal energy transport time.

These considerations have led us to conclude[1] that the relevant cross-field electron heat flux is the result of two different diffusive processes described as fast and slow. The slow process can be appropriately described by a term that is linear in the temperature gradient, but the fast diffusion is strongly determined by the departure of the electron temperature from the canonical profile and has a nonlinear temperature gradient dependence. In neither case is the magnitude of transport required to explicitly depend on the profile and strength of the electron thermal energy source. Expressing the total electron heat flux as $Q_e = -K(\kappa_S, \kappa_F)\partial T_e/\partial r$, we have analytically and numerically investigated two proposed forms for the effective conductivity K with regard to their ability to enforce profile consistency and generate fast heat pulse propagation. The coefficient κ_s is itself considered to be made up of two components. One is assumed to prevail in regimes where Ohmic heating is dominant, while the other is associated with microinstabilities driven by the electron pressure gradient and is taken to be responsible for the degradation of confinement observed in auxiliary heated experiments. The fast conductivity κ_F is chosen to be a finite multiple of the Ohmic transport. The specification of our model is completed by defining an edge boundary condition for T_e or, equivalently, giving a prescription for the central canonical temperature. A reasonable choice for edge temperature behavior is to assume that the profile is nearly canonical there.

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Relaxation of the High Density Z-Pinch to Self-Similar Behavior in the Presence of Inertia and Viscosity

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Computational models of the Fiber-Initiated High Density Z-Pinch (HDZP) have a tendency to approach self-similar behavior late in time.[1,2] This has been demonstrated previously by observing that for many functions of time $f(t)$ determined by inertial and transport simulation codes, $f/(df/dt)$ approaches a linear function of time. It has been interpreted by demonstrating that a limited subset of the 1-dimensional fluid equations governing the HDZP admits self-similar solutions. A detailed study of this behavior will be presented. New analytical and numerical results on the self-similar equations permit a more detailed understanding of their solutions and the use of these solutions as initial conditions for a full numerical simulation. The simulation, making use of moving finite elements, incorporates the effects of inertia, viscosity, radiation, and other nonideal effects. Results show that the solutions of the self-similar equations do not adequately characterize the simulation. The initial behavior diverges strongly from the initial self-similar solutions. The final behavior converges to a solution which appears self-similar but differs in important ways from the solutions of the simplified equations. Viscosity plays a strong role in this behavior. The uniqueness of the final state of the simulation cannot be accounted for by the multiplicity of solutions to the self-similar equations. The self-similarity of the final state is better than we have any right to expect from the equations.

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Sherwood Theory Conference
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Resistive g-Mode Steady Convection and Heat Transport*

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Steady convection arising from resistive g-modes in a tokamak and the associated heat transport are considered. For resistive g-modes, the free-energy source is the mean pressure gradient p_o' and the energy sink is molecular dissipation such as resistivity, viscosity and heat conductivity. Therefore when the mean pressure gradient surpasses a critical value p_c', modes localized on rational surfaces begin to grow. However, these modes eventually saturate with finite amplitude if the mean pressure gradient is not too large compared to the critical value and we have steady convection within a boundary layer, which is analogous to the Benard convection in fluid dynamics. This convection enhances the heat transport across the boundary layer and deteriorates the energy confinement of the plasma. We have shown by expanding the solutions in their small amplitude that the magnitude of the enhanced heat transport is proportional to $(p_o' - p_c')$ near p_c'. For p_o' away from p_c', when nonlinearity of the modes is strong, the anomalous heat transport due to the convection are determined by numerical simulations. It is shown that this anomalous heat transport can be much larger than the classical collisional heat conduction under some conditions.

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Effect of Partial Reconnection Sawtooth Model in Transport Simulations*

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Poloidal field profile measurements on TEXTOR[1],[2] and TEXT[3] suggest that the magnetic q-value can remain below unity in the central part of the plasma throughout the sawtooth oscillation period in tokamak discharges with moderate to low edge q-values. We examine consequences of sawtooth models in the 1-1/2-D BALDUR transport code in which the helical flux and current density do **not** completely rearrange themselves according to the Kadomtsev model,[4] while the temperature and density profiles are flattened during each sawtooth crash. We examine the effect of partial reconnection on the radial profile of the loop voltage, Ohmic heating power density, and the conversion of magnetic energy into thermodynamic energy during the sawtooth crash. The persistence of large shear throughout the sawtooth mixing region should also affect the stability of ballooning and pressure driven modes in the central part of elongated plasmas.

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INTERNAL KINK MODES IN SHAPED TOKAMAKS*

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A simplistic approach to β optimization, based on the Troyon-Gruber empirical scaling, would lead to highly elongated configurations. At the same time it is expected that elongation is in fact deleterious to the stability of the internal kink mode. Usually triangularity is invoked to stabilize the mode. It is therefore of interest to quantify the relative roles of elongation and triangularity in determining stability to the internal kink mode. This is done numerically for low aspect ratio tokamaks.

Profile effects play an equally important role. Many recent papers have addressed the role of shear in the vicinity of the magnetic axis. We shall review these effects as well.

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Ion Transport Theory Constraints on Linear Offset Scaling for τ_E*

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The scaling of the energy confinement τ_E in tokamak plasmas with auxiliary heating power P_{aux} and plasma current I_p is a central problem for the design of next generation burning plasma experiments. Here, we investigate the constraints provided by particle and energy balance equations describing impure $(n_z Z^2/n_i \sim 0(1))$ plasmas, in order to justify the proposed linear offset scaling $\tau_E \sim \mathrm{a}/P_{aux} + \tau_{incr}$ and the possible dependence of **a** and incremental confinement time τ_{incr} on I_p. As a first step, this is accomplished in the Shimomura-Odajima[1] scaling by eliminating the implicit temperature dependence of the Ohmic heating power. As a second step, we extend the approach of Callen et al.[2] (who ascribe the linear offset structure of τ_E to the convective piece of the total radial heat flux) by evaluating the case where χ_i is near neoclassical and the impurities strongly diffuse inward.

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SHERWOOD THEORY CONFERENCE
April 18 - 20, 1988

The Effect of Finite Pressure on Saturated Tearing Modes*

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In order to study the effect of saturated tearing modes in the 1-1/2-D BALDUR transport code, we use the quasi-linear method of determining island widths in a toroidal geometry developed by Bateman and Morris.[1] Numerical simulations based on this model have been used to examine the effects of global toroidal current density profiles, current suppression or peaking within the magnetic island, noncircular geometry, harmonic mixing, and proximity of the wall on the widths of the saturated tearing mode magnetic islands. We have extended this method to study the effects of a non-zero plasma pressure gradient on magnetic island behavior. Preliminary results suggest that the inclusion of pressure gradient terms yields an increase in island widths. We will also examime the effects of diferent sawtooth models, in which the magnetic q-value remains below unity at the magnetic axis, on the width of saturated tearing mode magnetic islands.

*This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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SHERWOOD THEORY MEETING 1988

Particle Simulation of Toroidicity-Induced Drift Modes *

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Although the universal mode in slab geometry is absolutely stabilized by any finite amount of shear, it has been argued[1] that in a toroidal system an unstable mode exists, which is known as the "toroidicty-induced" mode. The inhomogeneities in the poloidal angle in a toroidal system cause the modes at neighboring mode-rational surfaces to be strongly coupled for a given toroidal mode number n. Through fully kinetic toroidal simulation we have observed drift modes that become unstable and display strong coupling characteristics in the presence of toroidicity.

The plasma evolution is studied via the toroidal particle code,[2] which employs an (r, θ, ϕ)-type coordinate system and a nonuniform radial grid for enhanced radial resolution. Full ion dynamics and drift electron dynamics are modeled, and the electrostatic fields are calculated self-consistently. The magnetic field is prescribed by a vacuum toroidal component; the poloidal component is obtained through the given safety factor $q(r)$. For this simulation, only the $n = 9$ toroidal mode number was retained; poloidal mode numbers from $m = 5$ to $m = 15$ were also retained. The simulation employed 100,000 particles of each species, loaded with a gaussian radial density profile, and 128 radial grid points. Neighboring modes are strongly coupled with the perpendicular wavelength $k_\perp \rho_i \sim 0.2$ in the growth regime of theory.[3,4]

Analysis of the simulation data reveals a peak near each mode rational surface. Two or more observed drift wave signals are well-separated (in frequency) showing a band structure as multiple harmonics of the toroidicity-induced mode with the lowest harmonic $\omega/\omega^* \sim 0.26$, in reasonable agreement with linear theory. We see competition between global equilibrium variations and local coupling effects. The poloidal direction indicates a "ballooning" structure. The amplitude of the potential is observed to grow exponentially for the $m = 8$ through $m = 10$ poloidal mode numbers with $\gamma/\omega^* \sim 0.075$, which is a few times the linear theory value,[4] with trapped particles among the possible reasons for this (along with large m_e/m_i and large ϵ). Weak profile flattening occurred around the $m = 8$ to $m = 9$ surfaces until approximately the saturation time $e\phi/T_e \sim 0.04$ where $\rho_s/L_n \sim 0.1$; after this time no substantial modification was observed. Other nonlinear effects will also be discussed.

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Abstract for the 1988 SHERWOOD THEORY MEETING

1-D Modeling of Mode Beating OFCD in a Tokamak

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A one-dimensional (radial variation) model of the mode beating scheme of Oscillating Field Current Drive (OFCD) by Bellan et. al. (1,2) is presented. This model predicts significant DC current drive by small oscillations of toroidal and poloidal fields, even with movement of the plasma boundary accounted for, and without invoking reconnection, or non-conservation of plasma at the wall. The essential difference with (2) is the recognition that the toroidal electric field at the tokamak centerline is not identically zero when the transform $s=x/a(t)$ is applied there, i.e. the device centerline has non-zero velocity in the transform variable space. The transformation of the electric field must be included in all the variable space, not just where there is plasma velocity. This results in the VxB effect that is transformed out of the differential equation appearing in the boundary conditions at the device centerline and at the plasma boundary. Solutions for the magnitude of the effect and interpretation via Faraday's Law are presented.

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1988 SHERWOOD THEORY CONFERENCE

GROWTH RATES OF RESISTIVE BALLOONING MODES IN TOKAMAKS NEAR THE BETA LIMIT

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The calculation of growth rates of plasma instabilities in tokamaks near the beta limit is an important tool for interpreting the physical results obtained in present-day fusion devices. The detailed stability analysis of corresponding ASDEX equilibria, which were numerically calculated on the basis of experimentally determined current and pressure profiles, shows that the enhanced energy losses at high β_p can be explained with resistive ballooning modes.

This assessment of the resistive high-n stability was found in the framework of one-fluid MHD theory. Although the validity of this hydromagnetic model of the plasma is limited to modes with wavelengths much greater than the particle gyroradius and with growth rates faster than the diamagnetic drift frequency, it allows accurate inclusion of toroidal effects. Other features of the treatment of resistive ballooning modes are that high-accuracy MHD equilibria are used in order to correctly include the important effects of shear and curvature in the plasma boundary region near the separatrix, that complex growth rates are allowed, and that shooting methods for solving the related two-point boundary value problems on an infinite interval are avoided. The latter aspect results from the observation that, by taking a certain linear combination of the resistive ballooning mode equations, a variational approach can be found. Its computational realization consists in a rank-degradation analysis of the corresponding system matrix and was performed by applying an appropiately adapted inverse vector iteration procedure.

The main results may be summarized as follows: (1) The resistive growth rates show a strong increase if the plasma pressure exceeds the value observed in ASDEX; (2) resistive ballooning modes are unstable at arbitrarily small pressure gradients, albeit with an initially small growth rate. Beyond a certain value of the pressure gradient, these originally oscillatory-growing modes ($\mathrm{Im}\{\gamma\} \neq 0$) become purely growing and show a strong increase in $\mathrm{Re}\{\gamma\}$; (3) compressibility is strongly destabilizing. Only in the (unphysical) incompressible limit does an actual pressure gradient threshold for resistive ballooning modes exist.

Questions concerning the existence and attainment of a second resistive regime of stability are being investigated at present by analyzing high-beta, PBX-like plasma equilibrium configurations.

Ideal MHD Stability Marginal Points in TJ-II

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The flexibility of the TJ-II four-period heliac [1] derives largely from the hardcore winding, which is composed of a circular coil and a helical winding with separately controllable currents. In this way the rotational transform and the magnetic well can be controlled. (For example, in vacuum configurations the rotational transform per period can be varied by a factor 5, from $\iota_0/N = 0.16$ to $\iota_0/N = 0.78$).

Marginal points in ι with respect to the stability of selected modes obtained with FLERA [2] (FLux coordinate hERA) for a straight (helically symmetric model of TJ-II are investigated. The equilibria are calculated with the MOMCON code taking a large number of toroidal field periods [3]. The aspect ratio per period A=1/ha is kept fixed ($2\pi/h$: helical pitch; a_p : plasma radius) with a value A=2.5. This corresponds to the reference configuration with a_p= 0.15.

The (m,n) = (1,1), (2,2) modes for a $<\beta> = 0.02$ for different positions of the conducting wall and different values of N are considered and compared.

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HEATING OF SOLAR CORONA*

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A mechanism for solar coronal heating by Alfvén waves has been proposed[1] which invokes magnetic field line divergence in order to steepen Alfvén wave packets, create high current density, and lead to enhanced ohmic dissipation. In contrast to similar approaches,[2,3] the effect considered here is not due to density gradients or to magnetic shear, but to low-frequency magnetic turbulent fluctuations. While on the long spatial scale, the magnetic field lines are subject to a diffusion process, on the small spatial scale, they diverge exponentially, leading to a strong distortion of wave packets. It is shown that this effect leads to considerably more efficient conversion process of wave mechanical and magnetic energy to heat. It is therefore concluded that wave energy is absorbed within a few corona transits, before it leaks out of the coronal loop.

The low frequency structure of the magnetic field is also considered. A set of equations describing low frequency motion of flux tubes appropriate for numerical simulation is derived.

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SAWTEETH

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The quasi-periodic sawtooth phenomenon is studied numerically using a fully three-dimensional pseudo-spectral method. An earlier Strauss-equations code[1] is modified by adding a temperature equation and allowing the resistivity and thermal conductivity to evolve self-consistently according to the (isotropic, unmagnetized) Braginskii temperature dependences. A scalar viscosity is also used but no-slip boundary conditions are not enforced. A uniform external electric field is applied at the wall and the (square) poloidal boundary is held at a constant temperature. The runs last several hundred Alfven times.

Structured sawteeth are observed in such quantities as the kinetic energy and pointwise temperature and flow speed, and in many respects look realistic. A basically helical current channel is set up which involves a pair of helical ("$m = 1, n = 1$") counterrotating vortices,[1] sometimes called an "internal kink" configuration. The sawteeth are disturbances which are excited upon, and relax back toward, this persistent average helical configuration. They are not perturbations upon an axisymmetric state. This makes it confusing to try to describe them in terms of an essentially axisymmetric vocabulary, involving such variables as $q(r)$.

The emerging picture is one of unstable growth induced by steepening current gradients on the inside of the helical current channel. These in turn result from the decreasing resistivity in the hot central region. The temperature profile at the sawtooth minima is less helically deformed than the current channel. The unstable growth involves prominent $m = 2$ as well as $m = 1$ components in the kinetic energy, and continues until the velocity field is adequate to sweep the "hot spot" to the walls, occasioning the sawtooth "crash." The physical picture is not inconsistent with earlier interpretations, except that the helical nature of the background configuration raises questions about any possibilities for explanations in terms of perturbations on axisymmetric equilibria.

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DECIMATION OF THE BETCHOV MODEL OF TURBULENCE

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Kraichnan's decimated-amplitude scheme (DAS)[1] is applied to the Betchov random-coupling model of turbulence[2] in which the couplings obey properties directly related to those of fluid and MHD turbulence:

$$\frac{dx_i}{dt} = \sum_{j,k=1}^{N} C_{ijk}\, x_j x_k \qquad , \quad i=1 \ldots N \quad , \quad N \gg 1 \; .$$

The coupling coefficients are generated in triplets so that energy is conserved. For repeated subsrcipts, $C_{ijk} = 0 \Rightarrow$ ergodicity on the energy surface. All the modes are generated so as to be statistically symmetric. As $N \to \infty$, the DIA gives exact results[1,2] for the statistical properties of the Betchov model.

Because of the statistical symmetry, the full system can be decimated to a Langevin-like smaller subsytem with only S modes:

$$\frac{dx_i}{dt} = \sum_{j,k=1}^{S} C_{ijk}\, x_j x_k + q_i(t) \qquad , \quad i=1, \ldots S \; , \quad S \ll N \; .$$

where the stochastic forcing terms q_i must statistically represent the effects of the decimated modes and couplings. That is, we must enforce statistical equivalence ($\leftrightarrow$) between the forcing q_i and the directly computable term q_i^* in the decimated system

$$q_i(t) \;\leftrightarrow\; q_i^*(t) \;=\; w_i \sum_{j,k=1}^{S} C_{ijk}\, x_j x_k$$

where the weight factor w_i is chosen so that $< \Sigma_i q_i^2 > \; = \; < \Sigma_i q_i^{*2} >$.

For carefully selected moment constraints on the forcing q_i [average mean, variance, autocorrelation, and energy] we have achieved good results for low decimation levels[3] ($N = 96 \rightarrow S = 32$ modes). Strong decimations of 10^4:1 have been achieved when mean constraints of the form $<\Sigma_i q_i(t) x_i(t')>$ were imposed.

Preliminary comments will be presented for 2D MHD turbulence (where statistical symmetry now holds only within specific mode bands), as well as on the connection between DAS, DIA, RNG and transport models.

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A FLUID IONS-PARTICLE ELECTRONS MODEL FOR PLASMA INSTABILITIES*

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A hybrid model for simulating plasma instabilities of characteristic frequency less than the ion cyclotron frequency and the wavelength long compared with the ion Larmor radius is being developed. The main motivation is to study fluid-like modes, such as resistive g-mode turbulence and ion-pressure-gradient-driven turbulence, for which a fluid ion treatment is adequate but still retain the low frequency wave-particle electron resonances through a particle treatment of the guiding center electrons. For this purpose, Braginskii's fluid equations are used for the ions.[1] The guiding center electrons are treated as finite-size particles. Their parallel dynamics are treated exactly while their motion, perpendicular to the magnetic field, is given to lowest order by the $E \times B$ velocity. The equations are integrated in time using a two-step predictor corrector algorithm.[2]

The model has been implemented in 1-2/2D as well as 2-1/2D. Tests show that the model propagates sound waves correctly. Furthermore, density gradient drift wave instabilities in a shearless magnetic field have been studied using the multiple space scale expansion technique[3] to maintain the background gradients. The simulation results are in good agreement with theory for both the real frequency and the growth rate. The model is currently being applied to ion-pressure-gradient-driven drift waves.[4]

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Abstract Submitted for the
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Category: Plasma Equilibrium and Stability

Fast Equilibrium Calculations. S. W. Haney, J. P. Freidberg, Plasma Fusion Center, M.I.T.*— A fast fixed-boundary equilibrium solver, capable of computing a finite aspect ratio, finite beta dee or bean shaped equilibrium in less than a second on a Vax 11/780 computer and in a few minutes on a Macintosh personal computer, has been constructed. The solutions, while approximate, agree very well with exact two-dimensional calculations and may be useful for applications (such as parametric scans and between shot experimental data analysis) where speed, robustness, and ease-of-use are important considerations. The calculation is based on variational techniques. First, a variational principle describing a modified, but equivalent, version of the Grad-Shafranov equation is written. Second, a transformation to convenient "flux coordinates" is performed. Third, a series of trial functions representing flux surface and flux function shape are introduced. Finally, a Lagrangian is numerically minimized to yield the equilibrium.

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ASYMPTOTIC CALCULATION OF THE GEOMETRIC PHASE IN CLASSICAL MECHANICS

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It has been shown by Berry[1] that a quantum system whose hamiltonian undergoes an adiabatic evolution acquires a geometric phase, apart from the familiar dynamical phase. The classical analog of this geometric phase is known as Hannay's angle.[2] For quantum systems, in which the hamiltonian is changed at a slow but finite rate, Berry[3] has developed an iteration formula for the geometric phase. We formulate the analogous problem of calculating Hannay's angle to all orders by using Kruskal's asymptotic method for hamiltonians with quasi-periodic solutions. As an example of the method, we calculate Hannay's angle for the nonlinear oscillator treated earlier by Lewis[4] and Symon.[5] Recursive formulae are given for the geometric angle. The nonlinear oscillator is an interesting example in which the adiabatic approximation is exact.

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TOKAMAK TRANSPORT IN THE PRESENCE OF MULTIPLE MECHANISMS*

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Abstract

Some success has been achieved by Perkins, Tang, Waltz, and others in explaining tokamak transport using drift wave turbulence as the mechanism in the confinement region, $1 \lesssim q \sim 2$. Their solutions to the transport equations were obtained with the assumption that some unspecified mechanism—profile consistency—restricted the temperature in the edge region of the plasma. The present work has extended the analysis to include an edge region dominated by rippling modes and resistive ballooning modes with a confinement zone controlled by trapped electron modes. Analytic solutions can be obtained for the situation in which the source of particles decays exponentially into the plasma. The resulting global energy confinement times for ohmic plasmas exhibit some of the experimental features missing from previous analyses—a positive A_i dependence, owing to differences in neutral penetration, and no B dependence. The use of the rippling mode introduces a modest I dependence in the auxiliary heating confinement. When resistive ballooning mode losses are added, the confinement time at fixed density and device parameters is reduced by a factor of $\sim$ 1.2-2 times, supporting Bishop's theory of H-mode behavior. An alternative explanation of H-mode confinement improvement is a weakening of the rippling mode effect at high edge temperatures. The new model does not match ohmic or auxiliary confinement particularly well with respect to aspect ratio scaling. However, the model does lead to remarkably invariant temperature profiles—"profile consistency"? In conclusion, although the modes used do not have quite the right detailed dependence on some of the variables, they do have the correct general form.

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MODE-CONVERSION IN THE PRESENCE OF DISSIPATION FOR HEATING IN ICRF+

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ABSTRACT

Coupled wave equations, and the corresponding wave energy conservation law, describing the fast Alfvén and ion-Bernstein waves are derived for minority heating in ICRF. This full-wave system is subsequently reduced and approximately represented by means of two decoupled second-order systems of equations. One is a second-order o.d.e. for the fast wave [1] in which the ion-Bernstein mode is treated as a driven response. The second system is a coupled mode set of o.d.e's for the ion-Bernstein and fast Alfvén wave-amplitudes varying slowly under the effect of coupling, inhomogeneity and dissipation.

In high-field incidence the fast-wave transmission and mode-conversion coeffficients are given in closed form for arbitrary parallel (to $\vec{B}_0$) wavenumber. In low- field incidence the reflection coefficient is obtained from the second-order fast wave approximation and the mode-conversion coefficient is then determined from a relation correlating the coefficients. We obtain good agreement with results from numerical integrations of fourth-order o.d.e.'s that model the mode-conversion region.

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ALMOST TWO-DIMENSIONAL DRIFT WAVE TURBULENCE*

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Drift wave dynamics in strongly magnetized plasma has the property to be nearly two-dimensional : in the range $\omega/v_e < k_{||} < \omega/c_s$, both linear and nonlinear coupling coefficients depend mostly on the perpendicular wavenumber $k_\perp$ and only weakly on the parallel wavenumber $k_{||}$. It has been shown[1] however that the third (parallel) dimension plays an important role, by allowing a flow of energy to larger $k_{||}$, where it can be dissipated by ion Landau damping or ion viscosity. This effect has recently been further analysed[2] with the Direct-Interaction Approximation, and a theory has been developed which decouples the parallel and perpendicular dynamics. It gives firstly, the parallel fluctuation spectrum as a function of the perpendicular nonlinear decorrelation times, and secondly, the effect of the energy flow in the parallel direction on the perpendicular dynamics. The theoretical predictions have been tested numerically by comparing the full three-dimensional simulation of some low order drift wave turbulence model[3] and an effective two dimensional simulation which incorporates the former ideas. The results show excellent agreement, and open the possibility of performing large scale two-dimensional simulation of three dimensional phenomena. Domain of applications which are considered are drift wave, and ionospheric turbulence.

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SHERWOOD THEORY MEETING 1988

ICRF Wave Propagation through the Turbulent Edge*

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It is well known that the tokamak edge is highly turbulent with order one fluctuations and surprisingly long correlation lengths. This phenomena has been exhibited in numerous tokamak experiments; in particular, extensive experimental edge turbulence studies have been conducted on the TEXT tokamak[1,2]. Recently, the experimental findings have been understood reasonably well in terms of moderate m-number resistivity gradient driven turbulence including impurity radiation effects[3].

In this work we address the problem of ICRF wave propagation through the highly turbulent edge. It is demonstrated that significant effects can occur since edge turbulence contains dominant wavelengths on the order of the long wavelength incoming ICRF wave. Since the ICRF is several orders of magnitude greater than the low frequency edge turbulence, the calculation can be cast in terms of wave propagation through a turbulent medium. However, many complicating features are inherent in this analysis. In particular, the order one fluctuations in the edge indicate the need to perform a renormalized theory for the scattered wave. The theory is then represented in terms of a renormalized propagator and the correlation function for density fluctuations. Numerical support calculations as well as analytic calculations are presented.

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* Work supported by the U. S. Department of Energy under contract No. DE-AC03-76SF00098.

ELECTROMAGNETIC EFFECTS IN THE DETECTION OF ALPHA PARTICLES IN MILLLIMTER SCATTERING

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ABSTRACT

Under the electrostatic approximation, scattering parameters (choice of incident radiation, scattering and orientation angles) have been found from which the one-dimensional alpha particle distribution can be deduced from the experimental data. This deduction can be optimized by using incident millimeter radiation at forward scattering angles The choice of backward scattering angles or shorter wavelength (CO_2) radiation will make the deduction more difficult. Relativistic effects do not seem to be of importance because of the presence of Doppler broadening terms in the scattering function.

We generalize this treatment to include electromagnetic effects Electromagnetic effects will result in a reduced final signal if one intends to use millimeter scattering below the electron gyrofrequency frequency. In this case, the incident wave is an X-mode which is elliptically polarized. The results will be compared to those found by Bretz [PPPL *2396, October 1986] for a cold plasma.

TOK3D: A Model for 3d Resistive MHD Computations in Toroidal Geometry

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The 3d resistive MHD code, FRC3D[1], has been modified to toroidal geometry in order to model the nonlinear, resistive behavior of tokamaks with non-circular cross-sections (e.g. divertor tokamaks). The new code, TOK3D, uses the semi-implicit method to eliminate the fast mode time step constraint.[2] The semi-implicit operator may be applied in either split or unsplit algorithms. The unsplit algorithm is desirable when large vacuum regions are present. The split algorithm is most efficient and uses the technique of Uchimoto[3] in a leapfrog time advance. A stability analysis of this technique is presented to demonstrate the method's unconditional stability with respect to the fast modes. Results from applications of this code to tokamaks will be presented.

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Parameterization of the High-n Second Region of Ideal MHD Stability in Circular Boundary Tokamaks+

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The second region of stability to high-n ballooning modes is studied for circular outer boundary poloidal cross-section tokamaks. Equilibria with pressure profiles, $p(\psi)$, that are marginally stable to the second region at each flux surface are generated numerically by a two-dimensional equilibrium code which iterates with a high-n ballooning solver. This marginal stability constraint eliminates $p(\psi)$ as an independent variable in the calculation. The predictor variables of the analysis are then reduced to the tokamak parameters and the safety factor profile, $q(\psi)$, specified as $q(\psi) = q_o + (q_a - q_o) \psi^{\alpha_q}$, where ψ is the normalized poloidal flux, and q_o, q_a are the axis and edge safety factors, respectively. Both $p(\psi)$ and $q(\psi)$ are restricted to be monotonically increasing functions of ψ. The primary response variables considered are the basic plasma equilibrium figures of merit, β and $\varepsilon\beta_p$ which are generated for a large set of predictor variables. Simple analytic models are presented which reproduce the scaling of the marginally stable second region values of β and $\varepsilon\beta_p$, and stability diagrams illustrating the behavior of the high-n unstable region for various parameters are shown.

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PARTICLE SIMULATIONS OF LOW FREQUENCY FLUCTUATIONS IN FINITE BETA PLASMAS

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Linear theory and particle simulations of finite beta drift waves in shearless and sheared magnetic fields and of interchange modes in sheared magnetic fields have been carried out in slab geometry. The computer model used is a 2-1/2D guiding center electrons, full ion dynamics, magneto-inductive or Darwin particle simulation code. Only the shear Alfvén dynamics are retained in the model and perpendicular compressibility is ordered out. Results of linear theory and particle simulations are compared to each other and to their electrostatic counterparts. The growth rate of the shearless drift waves can be significantly reduced by finite beta effects. Reasonable agreement is obtained between theory eigenmodes and simulation ones in the sheared cases for both electrostatic and finite beta cases. Saturation of the interchange modes in the finite beta case is accompanied by field line bending.

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FORCED ALFVEN WAVE TURBULENCE AND SUBGRID SCALE CLOSURE

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Abstract

The method of renormalization group theory is applied to the problem of forced turbulence in the simplified Alfven model of Chen & Mahajan. The effects of small unresolvable subgrid modes on the large scale turbulence leads to a renormalized response function ε. In certain limits, the resulting recursion relation for the response function can be converted into a differential equation which can be solved analytically. For Gaussian forcing terms satisfying a power law wavenumber correlation k^{-y} but white noise frequency spectrum, it is found that the response function exhibits second harmonic generation of waves at frequency $\omega=2\Lambda v_A$ for all exponents $y \geq 0$, where Λ is the wavenumber separating the subgrid and supergrid modes.

SHERWOOD THEORY MEETING 1988

The Enhancement of Ion Neoclassical Heat Conduction due to Electron and Beam-Ion Energy Scattering Collisions*

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Due to pitch-angle scattering and ion orbits, passing ions at radius r with $v_{\|} < 0$ are strongly coupled to passing ions of the same energy and $v_{\|} > 0$ at $r + 2\delta r$ with $\delta r \sim (r/R)^{1/2}\rho_{i\theta}$. The tendency for these two groups of ions to equalize their rates of heating leads to extra components of ion heat conduction (q_i) driven by $C(f_{i1})$ and $\partial C(f_{i0})/\partial r$. For electron collisions

$$(q_i)_{ie} = -27\left(\frac{r}{R}\right) n_i \nu_e \frac{m_e}{m_i}\rho_{i\theta}^2 T_i' \left(1 - 0.48\frac{T_e}{T_i}\right) - \frac{29r}{R\Omega_\theta^2}\frac{\partial}{\partial r}\left[\frac{T_i}{m_i} n_i \nu_e \frac{m_e}{m_i}(T_e - T_i)\right] .$$

Both parts involve energy being taken from and then given back to the electrons at each diffusion step length. The first term involves an extra energy loss for the electrons; the second term involves part of the normal collisional energy transfer. For collisions with beam ions

$$(q_i)_{ib} = -0.48(r/R)P_{ib}\rho_{i\theta}^2 (T_i'/T_i) - 4.8(r/R)\rho_{i\theta}^2 \partial P_{ib}/\partial r ,$$

which will contribute to the deterioration of energy containment with auxiliary heating and with centralized heating. (P_{ib} is the ion heating rate per unit volume due to beam ions.) The above components of heat conduction will be increased substantially if the ions have a non-Maxwellian tail. In fact, the two collision terms $C_{ie}(f_{i0})$ and $C_{ib}(f_{i0})$ dominant at high ion energies and produce such a non-Maxwellian tail with effective temperature $T_H = T_e + (m_i P_{ib}/3n_i \nu_e m_e)$, enhancing all the components of ion heat conduction.

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

"Numerical Studies of RF Current Profile Control in Low Aspect Ratio, High Beta Tokamaks",*

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Recent theoretical investigations [1] have shown that with correct current profile control, second stability may be achieved in a modestly shaped tokamak provided $q(0) > 1$, and in particular $q(0) \gtrsim 2$, $q(a) \sim 7.6$, $\epsilon\beta_p \gtrsim 0.8$, and inverse aspect ratio of the order of $\epsilon \simeq 1/3$. The required current profiles in these discharges can be controlled through the use of RF driven currents, where a fraction of the total plasma current (I_p) is generated off-axis $(r/a \gtrsim 1/3 - 1/2)$. In this case $q(0)$ can be raised from unity to $q(0) \gtrsim 2$. This type of RF current profile control has been studied numerically [2] using lower hybrid (LH) RF driven current at $\bar{n}_e = 2 \times 10^{20}$ m^{-3}, $I_p \lesssim 120$ kA, $B_\theta = 1$ T, $P_{LH} \lesssim 0.5$ MW, and $f_o = 2.45$ GHz. These studies were carried out using a simulation model for LHCD [3] which utilizes a Shafronov equilibrium in the wave propagation and absorption package. At present, this calculation is being upgraded to a noncircular equilibrium and results for the wave propagation and absorption in the new equilibrium will be presented.

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Limitations on Aspect Ratio, q_0, and q_a Required for Stable Access to Second Stability in Tokamaks[1]

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A series of tokamak equilibria have been examined for stability to high n ballooning modes, and to ballooning and kink modes of $n = 1$, 2, and 3, for increasing β. As we reported previously[2], there is a path to second stability for a "D" shaped tokamak with current profile control, which is stable to all MHD ballooning and kink modes. The equilibria reported have an aspect ratio $R/a = 3$, a safety factor on axis $q_0 = 2$, and an edge safety factor $q_a = 8$. For stability to low n external kink modes, there must be a wall within 20% of the minor radius a from the plasma edge. The equilibria are physically reasonable, having monotonic current profiles and very low surface current. These results have been extended to other values of R/a, q_0, and q_a. It has been found that at a fixed global shear q_a/q_0, the stability is quite sensitive to aspect ratio. Raising the aspect ratio to 3.5, for example, results in an unstable region at intermediate β, unless q_0 is raised quite a bit (to 3 or greater), which makes the current profile control more difficult. Increased aspect ratio can also be compensated for by reducing the global shear. We will present results giving the limits on q_0 and q_a, as a function of R/a, required to have a stable path to second stability. We will also examine the dependence of stability on elongation, which has an optimal value, typically about 1.4, for a given R/a, q_0 and q_a.

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[1] Work supported by the U.S. Department of Energy under Contract No. DE-AC02-78ET51013.

[2] M. J. Gerver, J. Kesner, and J. J. Ramos, MIT Plasma Fusion Center Report PFC/JA 87-34, submitted to Phys. Fluids; also Bull. Am. Phys. Soc. **32**, 1773(1987).

SHERWOOD THEORY MEETING 1988

Exact Solutions of the Vlasov-Maxwell System *

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Interesting exact solutions of the Vlasov-Maxwell system describing plasmas with gradients are attained and their implications are discussed.

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

TOROIDAL SEMICOLLISIONAL MICROINSTABILITIES AND ANOMALOUS ELECTRON AND ION TRANSPORT

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The stability properties of the toroidal semicollisional microinstabilities driven by trapped electron dynamics and ion temperature gradients are analyzed using kinetic theory. Analytic dispersion relations are derived and discussed with a particular attention to the modelling of anomalous electron and ion thermal conductivity. The relation with previously derived models of anomalous transport and with the experimentally observed trends of the global energy confinement time is also discussed.

A Survey of Direct Linear Systems Solvers on the NMFECC System*

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We discuss the direct linear systems solvers available to users of the Cray machines at the National MFE Computer Center. We will outline and categorize the packages available on the on-line mathematical libraries OMNILIB, SLATEC, NAG and IMSL. We will also present some of our own highly optimized Cray-2 packages, including an assembly language version of a LINPACK banded Gaussian elimination solver and a highly parallelized cyclic reduction solver for multiprocessors.

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(*) 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.

THREE-DIMENSIONAL EQUILIBRIUM STUDIES OF AN UNCONVENTIONAL STELLARATOR DESIGN*

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We have been using the PIES three-dimensional equilibrium code[1] to study the properties of an unconventional stellarator first investigated by Freis *et al*[2] and by Furth and Hartman.[3] With stellarator windings only on the large-major-radius side of the torus, the stellarator differs from conventional ones both in the field coils used and in the resulting structure of the magnetic field. We compare our results with those of the previous analytical calculation[3], and we evaluate the advantages and disadvantages of the design relative to more conventional ones.

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*This work supported by U.S. DoE Contract # DE-AC02-76-CHO-3073.

Transport and Stability Considerations for the MICF Reactor*

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In the Magnetically Insulated Inertial Confinement Fusion[1] (MICF) system there are two plasma regions separated by a very strong, self-generated magnetic field which serves to thermally insulate the hot plasma core from the wall. The reactor potential of such a device depends critically on the particle and energy transport across the magnetic field in both directions, and on the stability of this high beta system. Since the core plasma in such a reactor will consist of several species (e.g., electrons, ions, thermal and fast alpha particles) each with its own temperature, we have addressed the relevant transport problem by calculating the particle and energy fluxes resulting from collisions between two different species at two different temperatures in the presence of density gradients. We also applied the stability criteria of Aydemir et al[2] and found that the system is stable to zero and finite FLR, temperature-gradient drift modes. The system is found to be unstable to density-gradient driven modes but the associated turbulence is found to be beneficial to the performance of the reactor. Such turbulence tends to promote efficient fuelling of the hot plasma which in turn results in the enhancement of the fusion energy gain i.e., the Q-value.

*Work supported by DOE

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SHERWOOD THEORY MEETING 1988

The Magnetic Field Lines on a Perfect Conductor or Circle Maps Generated by the Neumann Problem in a Torus

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The generic behavior that occurs in maps of the circle to itself serves as a unifying model for nonlinear physical systems with two competing periods. It has successfully modelled quasiperiodic, mode-locking, and chaotic phenoma in a variety of physical situations ranging from Josephson junctions to geophysics. A circle map is naturally generated by solving Laplaces equation in a topologically toroidal region with Neumann boundary conditions. The Neumann problem yields the magnetic field in a toroidal current free region, from which the field lines at the boundary are determined. These field lines define a map of the closed curve, defined by a poloidal cut of the boundary, to itself. For systems with symmetry separable solutions are easily obtained; these solutions are not particularly interesting. In the case without symmetry de Rham's theorem guarantees solutions with arbitrary periods; i.e. net toroidal and poloidal currents. We will discuss the kinds of solutions that can occur and their physical relevance.

STATISTICAL ANALYSIS OF ASDEX OHMIC PROFILES

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A systematic statistical analysis of 645 ASDEX datapoints is performed. The raw data is the toroidal magnetic field,total current,loop voltage, and electron density and temperature profiles. The database is limited to high density (>2.5), predominately low to moderate q discharges. Properties of good databases, profile parametrization, and quantitative measures of profile variance and invariance are discussed. Statistical methods and graphical repesentations are presented. By indexing each datapoint with a color and number a four dimensional parameter scan is possible.

The temperature profile is parametrized while similar representations of the density profile are not found due to the lack of apparent similarity of density profiles. The relative variation of the density and temperature profiles is analyzed statistically. Due to sawteeth, profiles are most accurately parametrized by rescaling the plasma radius from 1/q to 1.

The underlying databases is three dimensional, depending on q, total current and volume averaged density. The volume averaged temperature and input power are given as regressed quantities. Using Spitzer resistivity power balance calculations are performed. When we treat the electrons as the sole loss channel, we find that the electron heat conductivity in the good confinement region is approximately 1.35 m*m/sec , and is only weakly dependent on other parameters. This is related to our consideration of only shots at and above the density rollover in conefinement time. The constancy of chie implies constancy of conefinement time. Including theoretical models of neoclassical losses significantly alters this result and no clear local scaling is found.

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SHERWOOD THEORY MEETING 1988

Nonlinear Evolution of a Force-Free Arcade Field Driven by Shear Flow*

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In order to explain the phenomenon of the solar flare, we investigate analytically and numerically the time-evolution of a force-free arcade field driven by slow shear flow on a boundary. Under the assumption of helicity invariance, the force-free state is given by $\mathbf{J} = \alpha \mathbf{B}$, where $\mathbf{J}$ is the current density, $\mathbf{B}$ the magnetic field, and α the Lagrange multiplier. In the presence of the external force (viz., shear flow), α generally depends on space and time, as in the case of an RFP sustained by an external field.

In this work we extend the Woltjer-Taylor relaxation theory, introducing a linear transformation, $\alpha^2(\psi) = (a + b\psi)/(c + d\psi)$, where a, b, c, and d are adiabatic constants. (This transformation contains the constant-α case in the limit $b = d = 0$.) Noting that the magnetic energy must be finite with the boundary condition $\lim_{x\to\infty} |\psi| = 0$, we may choose α as follows, $\alpha(x, y, t) = \beta(t)\,(\psi/(\psi + 1/\beta))^{1/2}$, where the geometric parameter $\beta(t)$ represents the quasi-static stretching of the magnetic field line in the vertical direction due to the shear flow. From the force-free relationship, we have a nonlinear Grad-Shafranov type of equation, $\nabla^2\psi + \beta^2\psi + \alpha/2 \ln \left| \left(\sqrt{\psi + 1/\beta} - \sqrt{\psi}\right) \Big/ \left(\sqrt{\psi + 1/\beta} + \sqrt{\psi}\right) \right| = 0$. For large $\beta(t)$, the solution is $\psi \sim \cos ky \exp\left[-x\sqrt{k^2 - \beta^2}\right] \Big/ k$, where $k = 2\pi$ (with $Ly = 1$). If we may assume that this flux function approximately represents any force-free arcade field, we finally obtain $\beta(t) = k^2\xi \Big/ \sqrt{1 + (k\xi)^2}$, where $\xi(t)$ corresponds to the displacement at the foot point.

In order to compare our analytic solution with our simulation results, it is convenient to introduce the averaged global quantity $\tilde{\alpha}$ in place of $\alpha(x, y, t)$: $\tilde{\alpha}(t) = \langle \alpha \mathbf{B}^2 \rangle_V \,/\, \langle \mathbf{B}^2 \rangle_V$, where $\langle \text{- - -} \rangle_V$ means volume average. It is shown that the analytic solution agrees well with the resistive MHD simulations. This indicates that the force-free field evolves quasi-statically through a series of force-free states before reconnection occurs.

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A Linearized Resistive MHD Stability Code*

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A stability code (NOAH) is being developed that solves the linearized resistive MHD eigenmode equations for a given axisymmetric toroidal plasma equilibrium with noncircular flux surfaces. The approach being used has already been successfully applied to the linearized *ideal* MHD eigenmode equations in the NOVA code.[1] A specific formulation of the linearized resistive MHD eigenmode equations in toroidal geometry has been chosen on the basis of consistency with the tearing and interchange ordering and accuracy in resolving the continuous spectrum. By choosing a formulation which does not require lower order cancelation in order to resolve the continuous spectrum, the numerical errors caused by "spectral pollution" are avoided. A cubic B-spline finite element method is used to solve the linearized resistive MHD equations everywhere in the plasma, rather than using asymptotic matching between ideal and resistive regions.

Results from a code which implements the cylindrical limit of this formulation are presented. In particular, we investigate a low β tokamak equilibrium case for which asymptotic and shooting codes have previously been applied.[2] The accuracy of the code has been recently enhanced by circumventing problems that arise because the equations in become degenerate to lowest order at grid point located at the singular surface. Convergence studies performed on an interchange mode in a spheromak-like equilibrium show that modes found with Magnetic Reynold's numbers as high as $S = 10^{15}$ are converged with on the order of only 100 grid points, and agree with asymptotic matching code results.

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TRANSPORT AND ICRF MODELLING IN CIT WITH MAGNETIC FIELD RAMP*

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The Oak Ridge/Princeton WHIST/ICRF time-dependent transport and ray-tracing package has been updated to use the most recent version of the WHIST transport code. This coupling of the transport code with a ray-tracing package for calculation of the ICRF heating deposition profile produces a more realistic model of actual or future experimental plasmas. The transport section of the integrated package uses the more general MOMCON magnetic field representation and has a more accurate trapped-fraction calculation and improved physics in the diffusion coefficients. This updated code has been applied to a model CIT plasma with ICRF heating and a time-ramped magnetic field. We investigate the effects of a time-varying B-field, and thus a moving cyclotron resonance surface, on the ICRF heating efficiency.

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TOROIDAL 3-D MHD SIMULATION*

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A three-dimensional nonlinear MHD code, MH3D, has been written. This code solves MHD equations without any approximation. Toroidicity, compressibility, and resistivity, among others are included. This code is being used to study the m=1 mode and sawtooth oscillation in tokamaks, and stability of the helimak concept. The results of this study will be presented.

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Neutral Transport in a Time-Dependent Plasma Modelling Code Using the Multigroup Diffusion Approximation *

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Following the mutual interactions between neutral particles and plasma is important to the accurate modelling of plasma evolution on the transport time scale. Existing neutral transport codes, however, are either fast but too idealized (1D) for application to shaped plasmas, or realistic (Monte Carlo) but too slow for incorporation into a time-dependent modelling code. Recently it has been shown that the multigroup diffusion approximation to the neutral-particle transport equation is quite accurate.[1] Moreover, once the required macroscopic cross-sections are available, numerical solution of the associated 2D diffusion equations is sufficiently fast to make inclusion in a time-dependent modelling code feasible. Unfortunately, calculation of the cross-sections, which must be done whenever the plasma temperature or density changes, is very time-consuming.

To circumvent the latter problem, I've written a new macroscopic cross-section package that factors out the dependence on plasma density and constructs cubic-spline fits to the dependence on ion and electron temperatures. After this code is run once, subsequent recalculation of all group constants requires a negligible amount of time. Multigroup diffusion thereby becomes an attractive method for the treatment of neutral-particle effects in an iterative global modelling code.

To solve the multi-group diffusion equations, a new solver based on isoparametric quadrilateral finite elements is under development. The resulting code will model the transport of neutral molecules and atoms in a 2D cylindrical plasma surrounded by a recycling wall and intervening vacuum region. Preliminary results will be presented.

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

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M. Z. Hasan and R. W. Conn, J. Comput. Phys. **71**, 371 (1987)

On the Connection between Micro- and Macrostability and Sawtooth Oscillations in Tokamaks

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In recent experiments on the Joint European Torus, sawtooth oscillations have been observed to have a qualitatively different character than in earlier experiments. The sawtooth crashes have been seen to occur on the ideal, rather than the resistive time scale. In a number of experiments[1] with the ICRF heating, sawteeth are characterized by both larger amplitude and longer period that in the purely ohmically heated case. The amplitude and the period appear to increase with the ICRF power. It has been suggested[2] that this behavior may be caused by a ponderomotive stabilization of the ideal internal kink mode which is responsible for the sawtooth crash. However, this model does not seem to describe the so-called "monster" sawteeth[3]. In particular, the monster sawtooth crash does not occur immediately after the ICRF is turned off. The delay time ~ 30 ms is much longer than the MHD time scale on which the sawtooth crash is seen to occur. This appears to contradict the ponderomotive stabilization hypothesis. As an alternative, we explore the possibility that ponderomotive stabilization is still present after the ICRF heating is turned off but now is caused by ion-cyclotron waves generated by a plasma microinstability rather than external antennas. Such a microinstability could be driven by the anisotropic velocity space ion population which has been seen in the plasma core on JET and which is subject to Alfven-ion cyclotron instability. We employ the resonance broadening theory of this instability in order to estimate both saturated wave amplitudes and the diffusion coefficient. We find that saturated wave fields are on the order of fields required to stabilize the internal kink and the estimated isotropization time is comparable to the observed delay in the sawtooth crash. We also speculate about other circumstances when the plasma microinstability may affect the macrostability via ponderomotive stabilization mechanism.
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Electron Transport Near a Separatrix and the H–Mode

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In previous work [1,2], the role of ion transport in obtaining H–mode discharges in diverted tokamak plasmas has been investigated. This theory is now extended to the electrons. The plasma in the scrape-off layer, just outside the separatrix, typically has a low temperature ($T_e < 100$ eV) and a large safety factor ($q \sim 10$). The magnetic field lines are open, and in thermal contact with the vessel walls at the divertor. This causes a substantial poloidal temperature gradient to develop in the scrape-off layer plasma. The poloidal temperature gradient modifies the radial electron heat flux through a classical thermal pinch:

$$q_{er}^{cl} = -\,\frac{5}{2}\,\frac{cP_e}{eB^2}\,\left(\vec{B} \times \vec{\nabla} T_e\right) \cdot \vec{e}_r \quad .$$

A poloidal thermoelectric field is also generated by the temperature gradient ($n_e \alpha \nabla_{\parallel} T_e = -\, e n_e E_{\parallel} - \nabla_{\parallel} P_e$), which in turn produces a radial electron flux through an $\vec{E} \times \vec{B}$ pinch:

$$\Gamma_{er}^{cl} = -\,\frac{c}{eB^2}\,\vec{B} \times \left(\vec{\nabla} P_e + e n_e \vec{E}\right) \cdot \vec{e}_r \quad .$$

The conditions in the scrape-off layer are such that these classical radial flows can be of comparable size to the anomalous fluxes. In particular, the inward pinch due to the thermoelectric field is large enough to explain the density rise observed during H–mode discharges. A detailed comparison with the data from DIII–D is made, and the relative strengths of the classical and anomalous fluxes are determined. A picture of the L to H transition emerges, with the behavior of the anomalous transport prescribed by self consistency.

This is a report of work sponsored by the U.S. Department of Energy under Contract No. DE-AC03-84ER53158.

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Ion Heat Flow in a Model Divertor Configuration

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The nonlinear partial differential equation describing ion heat flow in a model divertor configuration has been solved numerically. This extends previous work [1] which used sources and sinks to represent the x-point effects. Those aspects of the problem which make the numerical solution most challenging also make it interesting physically. The equation is a two-way diffusion equation, with the temperature inside the separatrix being influenced only by those boundary values outside the separatrix which are in a limited range of poloidal angles. The dependence of the solution on the ion grad-B drift direction thus appears in a very fundamental way. The boundary conditions are of a type typical of boundary layer problems, and cause the poloidal dependence of the solution to change in a thin layer near the separatrix. The nonlinearity of the thermal conductivity makes the poloidal temperature gradient largest near the x-point, so the poloidal localization of the effective heat sink depends strongly on the nonlinearity. The results of the calculation show clearly that a temperature pedestal develops when the ion grad-B drift direction is toward the x-point.

This is a report of work sponsored by the U.S. Department of Energy under Contract No. DE-AC03-84ER53158.

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MAGNETIC FLUX LOSS IN A FIELD REVERSED CONFIGURATION

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The flux confinement time and particle confinement time observed in Field Reversed Configurations (FRC's) are shorter than the times predicted from theories involving classical transport. Microturbulent fluctuations are expected to be present in such a plasma and are thought to provide the enhanced transport demanded by the observations, although the agreement between observations and theories involving microturbulent transport is not altogether satisfactory. The enhanced transport at the O point and at the separatrix may be due to microturbulence generated locally in each separate region (involving different instabilities), and/or it may be due to microturbulence which is generated in one region and then propagates over the entire plasma. In principle, the separatrix region should be a copious source of microturbulence because of the steep density gradient maintained there. Such gradients are known to drive the Lower Hybrid Drift Instability (LHDI). Linear theories of the LHDI in a reversed field configuration have shown that the unstable eigenfunction penetrates toward, but not to, the O point, while nonlinear simulations have suggested that penetration to the O point can occur for an artificially low value of the ion to electron mass ratio, but not for the correct one.

This research examines the microstability properties of a Field Reversed Plasma having infinite axial extent and planar (as opposed to cylindrical) geometry. The plasma is evolved with a finite-electron-mass hybrid code in which the ions are kinetic and the electrons are a finite mass charge neutralizing fluid. Waves characteristic of the lower hybrid drift instability quickly grow in the region near the separatrix where the driving density gradient is large. These waves soon become nonlinear and then penetrate to the region of the field null. As the simulation is run for longer times, lower frequency waves enter the simulational domain and interact with the higher frequency ones. Although, no classical Coulomb collisions are included in the model, magnetic flux is nevertheless destroyed at later times, indicating the presence of a microturbulent resistivity at the field null. We will quantify the magnitude of this resistivity and compare it with what is required to match the experimentally observed flux decay time.

Production of Non-Thermal Electrons by Electron Cyclotron Heating in ATF

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Using a 2D Fokker-Planck code[1,2] the electron distribution function $f(p_\perp, p_\parallel, t)$ is obtained from the solution of the kinetic equation

$$\frac{\partial f}{\partial \tau} = \frac{1}{u_\perp}\left(\frac{\omega_c}{\omega}\frac{\partial}{\partial u_\perp} + \frac{u_\perp}{\mu^{1/2}}\frac{\partial}{\partial u_\parallel} n_\parallel\right) u_\perp D_{cy}\left(\frac{\omega_c}{\omega}\frac{\partial}{\partial u_\perp} + \frac{n_\parallel u_\perp}{\mu^{1/2}}\frac{\partial}{\partial u_\parallel}\right) f + \left(\frac{\partial f}{\partial \tau}\right)_{coll}$$

where $\tau = \upsilon_e t$, $\upsilon_e = 2\pi e^4 n_e \Lambda / m^{1/2} T_e^{3/2}$, Λ is the Coulomb logarithm, $\mathbf{u} = \mathbf{p}/(mT_e)^{1/2}$, and $\mu = mc^2/T_e$.

The non-thermal characteristics of EC and X-ray emission spectra obtained for the computed distribution function are discussed. A comparison with the usual analytical models is presented.

The plasma parameters used are those of the Advanced Toroidal Facility[3].

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IDEAL LOW-n AND MERCIER STABILITY BOUNDARIES FOR $l = 2$ TORSATRONS*

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We have studied the relation between the stability properties of the low-n internal modes for torsatron configurations and the 3-D Mercier criterion. We have found that: 1) the low-n modes with singular surfaces lying in a Mercier unstable region are in general unstable; and 2) the critical β given by the Mercier criterion agrees well with the β threshold for the lowest n unstable mode. The latter is verified even in the case of global $n = 1$ modes. Therefore, for torsatron configurations the 3-D Mercier criterion is a useful guide in mapping the stability β limits. This study has been carried out for several torsatron configurations, exploring a broad range of aspect ratios and different pressure profiles. For the low-n stability studies, the stellarator expansion[1] has been used as is implemented in the FAR code.[2] The 3-D Mercier criterion has been applied to the equilibria calculated with the VMEC code.[3]

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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EFFECT OF DENSITY FLUCTUATIONS ON ICRF HEATING OF TOKAMAKS*

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Fast wave heating of tokamaks in the ion cyclotron range of frequencies (ICRF) has yielded the highest experimental heating rates in the fundamental-minority regime of operation. The dominant physical processes in this heating scheme are: 1) direct (cyclotron) absorption of the launched wave energy by the minority species (usually H), 2) majority species (usually D) heating due to second harmonic absorption, 3) mode conversion into an ion Bernstein wave (IBW), and 4) electron heating due to Landau and transit time damping. The efficiency of these processes is known to depend critically on the ratio of the densities of the minority and majority species. Motivated by the experimental observation of large density fluctuations in tokamak plasmas, we have developed a model to investigate their effect on ICRF heating. The model consists of a slab plasma in which the perpendicular (with respect to the equilibrium magnetic field) gradients (density, temperature, and magnetic field) are taken into account self-consistently[1]. As a first approximation, the density fluctuations are modelled by adding to the equilibrium configuration a sinusoidal density ripple whose amplitude, wave number and phase can be varied. The effects due to majority density fluctuations have been investiigated for low and high field excitation. In both cases, the dominant process is enhanced reflection of the fast wave due to backscattering. The effect of pure minority density fluctuations shows marked differences between low and high field excitation. For low field incidence the strongest modification occurs when the wavelength of the fluctuation is approximately equal to the unperturbed width of the hydrogen absorption curve. Large changes in the minority absorption coefficient can occur depending on the phase of the fluctuation. This is due to the rearrangement of the resonant particles in the absorption region. For high field incidence, the mode conversion coefficient approaches zero (and the reflection coefficient unity) when the wave number of the fluctuation is approximately four times the asymptotic wave number of the fast wave.

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SHERWOOD THEORY MEETING 1988

Heating of Two-Component Plasma in the Fundamental Minority Cyclotron Range of Frequencies*

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In this work, we consider ion cyclotron range of frequencies (ICRF) heating in the minority-carrying plasma where the transmitted frequency is near the minority fundamental in the interior of the plasma. This is initially motivated by noting that a minority fundamental that is below the majority fundamental can resonate within the Alfvén range of frequencies. Thus, the minority can strongly affect the Alfvén wave heating. To be considered are the following three special examples: (1) oxygen minority in the small PRETEXT tokamak, (2) T and H minority in deuterium in the large TFTR tokamak. Two cylindrical models consisting of either (a) a radially varying minority charge profile or (b) a radial variation of a toroidal-like equilibrium magnetic field are used to induce a fundamental minority gyroresonance. The results including the minority effects on the Alfvén wave and ICRF heating will be presented.

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PREDICTIONS OF THE ION TEMPERATURE GRADIENT (η_i) MODE IN THE COLUMBIA LINEAR MACHINE*

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ABSTRACT

The Columbia Linear Machine (CLM) is being redesigned to produce and identify the ion temperature gradient driven η_i mode. Using the expected parameters, we have developed detailled predictions of the mode characteristics in the CLM, based on elaboration on and generalization of previous linear theories[1,2]. These include the growth rate and real frequency as a function of of the azimuthal mode number m, the drive parameter $\eta_i = d(LnT)/d(LnN)$ and the parallel wave number $k_{\parallel}$. The latter two parametric dependances can be verified experimentally via variable phasing of two double half turn ICRH antennas and endplate locations, respectively. We find that, for typical parameters, $\eta_{i\ crit} \approx 1.2$ to 1.8, which is easily achievable experimentally. Furthermore, the growth rate normalized to the electron diamagnetic drift frequency $(\gamma/\omega_e^*)_{max} \approx 20$ per cent, which indicates a strong instability. As both the ion temperature and density gradients are significantly variable over the expected radial wave length of the mode, we have developed a non-local radial differential equation. With some approximations, this can be reduced to a Weber type equation, which has been solved. The result will be compared to that of a local dispersion relation. A comprehensive physical picture of the instability has also been derived.

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Magnetic Fluctuations Due to Thermally Excited Alfvén Waves*

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Magnetic fluctuations due to the thermally excited MHD waves are investigated using fluid and kinetic models to describe a stable, uniform, compressible plasma in the range above the drift wave frequency and below the ion cyclotron frequency. It is shown that the fluid model with resistivity yields spectral densities which are roughly Lorentzian, exhibit equipartition with no apparent cutoff in wavenumber space and a Bohm-type diffusion coefficient. For a phenomenological cutoff imposed on the spectrum, the typical fluctuating-to-equilibrium magnetic field ratio is found to be of the order of 10^{-6}. Physical cutoffs due to dispersion and/or different forms of damping are investigated numerically in terms of a kinetic model. It is found that the amplitude of fluctuations may be below the value suggested by the cold plasma model by orders of magnitude. However, even the small levels of fluctuations may lead to induced diffusion comparable to the classical values. The results from both models are presented and compared in low- and high-β regimes.

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Poloidal Field Effects on ICRH in Large Tokamaks*

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ABSTRACT

We consider a tokamak plasma where geometrical optics provides a good approximation for wave propagation, except possibly near resonance surfaces. When the effects of a small equilibrium poloidal field are included, we find that within the cyclotron resonance layers the current becomes a nonlocal functional of the equilibrium magnetic field. We solve the linearized Vlasov equation to determine this current using a boundary layer analysis. When this current is substituted in Maxwell's equations we find that the field equations transform into a system of integro-differential equations. Moreover, the usual assumption of the perpendicular stratification no longer holds in this case. We show that asymptotic solutions of this field equation are linear combinations of geometrical optics modes, and we construct full wave solutions of scattering problems by determining these linear combinations. We first consider the case of minority ion fundamental cyclotron resonance, where there is only one ion species in resonance in the layer. We solve the corresponding field equation numerically for the case of fast mode incidence from the high or low field sides. We verify the results of previously established theorems that (i) the transmission coefficient is independent of the direction of the incidence, (ii) its value is the same as that predicted by geometrical optics, and (iii) there is no reflected wave when the incidence is from the high field side. There are no Bernstein modes within the layer in this case, and thus no mode conversion occurs. Numerical results indicate that in the case of low field side incidence the poloidal field effects can reduce the reflected energy significantly (up to 50%) thus providing a good heating even at temperatures of a few keV. As a second problem, we consider the case of second harmonic ion cyclotron resonance with or without minority species at fundamental resonance. In this case the reciprocity theorems apply between the (real) adjoint problems, which differ only by the orientation of the poloidal field. The field equations valid within the resonance layer are in the form of a fourth order integro-differential system, signaling the existence of Bernstein modes. The solutions of this system are asymptotically similar to the results of the local theory. Our numerical method is based on the construction of a right hand side for the local system, so that the solution of the modified system is also the solution of the nonlocal integro-differential system. We present the results of this study.

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Simulation of Collisionless Magnetic Reconnection with Realistic Ion to Electron Mass Ratio

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The basic physical phenomena associated with collisionless magnetic reconnection are investigated with the implicit PIC code AVANTI.[1] AVANTI is based on a 2.5-D fully electromagnetic direct implicit algorithm which has proven stable for arbitrary time step. This code is ideally suited for studies of magnetic reconnection because of this increased flexibility in time step selection. High frequency electron plasma oscillations that are immaterial to magnetic reconnection need not be resolved numerically. Similarly, purely electromagnetic modes are unimportant in this process and are not resolved. We select the appropriate time step needed to give detailed resolution of electron gyro-motion and other particle-field interactions that are important to collisionless reconnection. We have exploited this new advantage to simulate physically realistic ion to electron mass ratios that reveal qualitatively new behavior.[2] The reconnection process is found to occur in three distinct stages: 1) early spontaneous reconnection fed by the free energy of an initial anisotropy in the electron component, 2) coalescence of the resulting small scale filaments of electron current, accompanied by an enhanced growth rate of trapped magnetic flux, and 3) oscillatory flow of electrons through the magnetic X-point, superimposed on continuing non-linear growth of ion-mediated reconnection. This oscillation of electrons and their associated magnetic flux is found to occur only for large ion to electron mass ratios (≥ 200), and has therefore not been seen in previous numerical simulations with explicit codes. It is caused by the dynamic interaction between the $\mathbf{E} \times \mathbf{B}$ drift of the magnetized electrons (but not the ions) into the magnetic island and the electrostatic ambipolar potential which eventually forces ions to follow electrons through the X-point. The time-asymptotic growth of trapped flux is shown to scale with the ion-sound velocity, $v_s = \sqrt{T_e/m_i}$.

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SENSITIVITY OF TRANSIENT SYNCHROTRON RADIATION TO TOKAMAK PLASMA PARAMETERS

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Brief, but intense, resonant wave heating of high energy electrons can produce in tokamaks a transient synchrotron radiation response that is distinguishable from the steady background radiation. The radiation response, a two-dimensional pattern in frequency-time space, is highly sensitive to the details of both the heating pulse and the plasma parameters. For example, the radiation associated with the wave-heating of high-energy electrons tends to be at lower frequency and to decay more slowly than radiation associated with the heating of low-energy electrons. More precise details of the radiation pattern, however, are governed by e.g., the plasma density, the effective ion charge state or the observation angle with respect to the magnetic field.

Quite gross characteristics of the radiation response can be used to deduce the heating and plasma parameters. By gross characteristics, we mean those that reflect primarily the two-dimensional shape of the radiation response and are largely insensitive to noise or calibration errors. It turns out, in fact, that the gross characteristics of the radiation are sufficient to allow simultaneous deduction of several heating and plasma parameters of interest. Thus, we are not limited to the case where only one parameter is considered unknown.

In this work we restrict ourselves to the steady-state plasma (no dc electric field), and we identify the plasma properties that can be reliably extracted through observation of the transient radiation. To evaluate this diagnostic technique, we simulated experimental data by corrupting the theoretically computed values with gaussian uncorrelated noise. Noise levels as large as 30% of the peak value of the expected radiation still allow the simultaneous deduction of the correct set of values for Z_{eff}, θ (the viewing angle relative to the magnetic field), u_0 and Δu_0 (the location and width of the perturbation in velocity space). The resolution of the viewing angle is limited by the optical system (to about 1° or 2°) rather than by the level of noise. To the extent that the angle θ is resolvable, information concerning the local value of q is obtainable.

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Transport in a Moderately Large Aspect Ratio, Near Circular Cross Section Tokamak*

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In a paper with W. Kerner (Tokamak Transport Based in the Braginskii Model, Z. Maturforsch. 42a, 1101-1114 (1987)), we presented the general outlines of a transport calculation in a moderately large, hot tokamak. By treating the electron and ion flows carefully and by including the parallel viscosity carefully, we found that we could estimate transport lifetimes consistent with present experiments. Our analysis is similar to that of Callen et al (Nuclear Fusion, IAEA-CN-471E-II-3-2, p. 157), but our flows and equilibria are significantly more general. In order to explore the content and significance of our model we have applied it to the case of a moderately large aspect ratio, near circular cross-section tokamak. By expansion in the appropriate parameters we can find relatively simple explicit expressions for the time evolution of the state of the tokamak and we give these expressions. We also examine the condition for a steady state tokamak.

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1D36

SIMULATION OF TOROIDICITY IN A LINEAR HELIAC

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The vacuum magnetic field of a heliac is calculated to first order in the inverse aspect ratio. The expansion also includes, to the first order, a shift of the hard core system relative to the $\ell = 1$ external coils as a second desymmetrizing effect. Puncture plots of the vacuum field lines and the Boozer harmonic content of the field strength on flux surfaces are used to compare these two desymmetrizing effects. Results show that the hard core shift provides a very good simulation of toroidicity. Further, an appropriate inward shift of the hardcore is found to cancel toroidally induced loss of flux surfaces and induced field ripple. The extension of these results to finite β is discussed.

Resistive Infernal Modes*

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When the safety factor profile is made extremely flat over a region of the plasma near the magnetic axis so that the shear becomes sufficiently weak, the growth rate as a function of q_0, the safety factor at the magnetic axis, becomes very peaked at some value of q_0. This instability is driven by the rational surface given by $q_0 = m/n$, where n is the toroidal wave number and m is the poloidal wave number. This high n instability (for this study $n = 3$ was used) has been called the infernal mode[1] and can exist even when standard ballooning theory predicts stability. It is ideal and pressure driven becoming stable if β is reduced. Equilibria with β's just below β_c (the value of β required to just destabilize the infernal mode) have been studied using the resistive MHD code FAR.[2] These equilibria are found to be resistively unstable. An analytic analysis was done which established the scaling of the "resistive infernal mode" growth rate with S (the ratio of resistive to poloidal Alfvén times). This scaling differs depending on the parameter.

$$\tilde{\gamma} = m\left[\frac{(\delta q^2 - \delta q_c^2)}{(1+2q^2)}\right]$$

where q is the value of the safety factor at the rational surface driving the instability, $\delta q = q_0 - m/n$ and δq_c is the value of δq required for ideal stability. For $\gamma \gg \tilde{\gamma}$, $\gamma \propto S^{-3/13}$ and for $\gamma \ll \tilde{\gamma}$, $\gamma \propto S^{-3/5}$, with γ in units of inverse poloidal Alfvén times. Both of these scalings have been found numerically. The mode with $\gamma \gg \tilde{\gamma}$ is essentially the resistive continuation of the ideal infernal mode and thus has a very broad character while the mode with $\gamma \ll \tilde{\gamma}$ is a separate branch with a localized tearing character. The scaling of one of the modes is sufficiently weak $(S^{-3/13})$ that the growth rates are appreciable even for JET/TFTR parameters $(S \approx 10^8)$. Details and additional results will be presented.

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Sawtooth Stabilisation in the Presence of Energetic Ions

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ABSTRACT

A theoretical model is proposed to explain the suppression of sawtooth oscillations in the JET tokamak during intense ion cyclotron radio frequency heating. Central in our analysis is the observation that, during the sawtooth free period (the so-called "monster sawtooth" regime), the value of the q parameter on the magnetic axis as obtained by Faraday rotation measurements drops significantly below unity. In addition, high poloidal betas ($\beta_p > 0.3$) in excess of the predicted threshold for the excitation of resistive, and frequently even ideal, m = 1 internal modes are attained. As these modes are generally believed to be the cause of the sawtooth crash, we have investigated the possibility that their improved stability is due to the presence of high energy anisotropic ions (with $p_\perp > p_{||}$) accelerated by the rf fields.

We find that the trapped hot ions introduce a new threshold for the m = 1 instability by modifying the pressure response in the central region of the plasma where q < 1. The stabilisation mechanism arises because the magnetic drift motion of these ions is faster than the phase velocity of the m = 1 mode. In this frequency range, energy must be spent to perturb the hot ions, a process which has been invoked in the past to stabilise MHD fluctuations in ion ring devices and other machines such as Astron.

In discharges where the highest values of β_p are attained, the appropriate stability condition is:

$$\beta_{p,h} \equiv - \frac{8\pi}{B_p^2(r_o)} \int_o^{r_o} dr \left\{ \left(\frac{r}{r_o}\right)^{3/2} \frac{d}{dr}\left[\left(\frac{r}{r_o}\right)^{1/2} p_{\perp h}\right]\right\} > \alpha \frac{r_o}{R_o} \frac{\langle\omega_{Dh}\rangle}{\omega_{*i}} \beta_p^2 .$$

where r_o is the effective q = 1 radius, $p_{\perp h}$ is the transverse hot ion pressure, $\langle\omega_{Dh}\rangle$ is the bounce average magnetic drift frequency at the mean value of the trapped hot ion energy, ω_{*i} is the bulk ion diamagnetic frequency, and α is a numerical factor of order unity which is primarily determined by the actual q profile. For reasonable estimates of the hot ion distribution function, this condition is numerically consistent with the experimentally measured values of the relevant parameters. In addition, it reflects the fact that monster sawteeth are very difficult to obtain with off-axis rf heating, since this is be likely to produce a profile of $p_{\perp h}$ which is not sufficiently peaked within the q = 1 surface to yield a positive $\beta_{p,h}$.

SAWTOOTH STABILIZATION BY ENERGETIC TRAPPED PARTICLES*

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Recent experiments involving high power radio-frequency heating of a tokamak plasma show strong suppression of the sawtooth oscillation. We have investigated the resistive kink mode dispersion relation, including diamagnetic effects, as modified by a trapped hot particle population.[1] Both the usual $m = 1$ tearing mode branch and the fishbone branch were studied as a function of the trapped particle energy, and density, and the Reynolds number, as well as ion and electron diamagnetic frequencies. A high energy trapped particle population is shown to have a strong stabilizing effect on the internal resistive kink mode. The stabilization is proportional to the high energy trapped particle density, and results in more than an order of magnitude decrease in the growth rate for the densities achieved during ICRF heating on JET.[2]

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Toroidal Studies of Sawtooth Oscillations in Tokamaks*

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An extensive study of sawtooth oscillations in tokamaks has been conducted using a fully toroidal resistive MHD code. This work extends our earlier linear and nonlinear studies of low-shear equilibria[1] to a self-consistent regime where periodic sawtooth oscillations are followed on a transport time scale. Long-time-scale studies of this nature using compressible, full MHD equations have become feasible because of highly efficient implicit techniques developed only recently[2].

Some of the important points to be discussed are as follows:

1. In agreement with Denton et al.[3], perpendicular transport is found to play a crucial role in the type of sawtooth oscillations observed. For a constant thermal conductivity coefficient, $\kappa_\perp$, typically simple sawtooth oscillations with a Kadomtsev-like crash are seen. After the crash, the temperature profile is hollow, and $q > 1$ inside the inversion radius. During the ramp phase of the sawtooth, the temperature profile peaks up due to ohmic heating, while $q \rightarrow 1$ from above. Wesson's "quasi-interchange" mode[4], with its characteristically parabolic eigenfunction goes unstable during this phase. However, q_o continues to drop, and the increasing shear converts the mode into a finite-β resistive tearing mode, which eventually leads to the crash. Scaling studies indicate that the sawtooth period increases linearly with S,whereas the crash times scale as $S^{1/2}$.
2. With more general $\kappa_\perp$ models, we have been able to produce other types of sawtooth oscillations, including subordinate crashes, and giant crashes with $\Delta T/T \sim O(1)$.
3. Modifying $\kappa_\perp(r,\theta)$ without increasing $\epsilon\beta_p$, we have been able to produce finite-β modes with a ballooning character. Scaling studies are under way to determine if these modes can account for the fast crashes observed in large tokamaks.
4. Sawtooth oscillations are generally believed to affect only the central region, without significantly modifying the global energy confinement. However, our studies indicate a high level of crash-induced stochasticity in the magnetic field lines that may play a role in the overall confinement degradation through parallel electron transport. In this context, we have done heat pulse propagation studies in which $\kappa_\perp^{HP}$, the effective perpendicular thermal conductivity for post-crash heat pulse propagation, exceeds estimates based on 1D diffusion models by a factor of 4-5.
5. Some of these points will be illustrated with a computer-generated movie.

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THEORETICAL UNDERSTANDING OF JET MHD BEHAVIOUR

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The mhd behaviour of JET includes several unexpected features. There are new observations which require a theoretical explanation and there are also more familiar phenomena which call for a re-appraisal of the conventional theory.

The talk will summarise the present understanding of four subjects.

1. Sawteeth and monster sawteeth - the conflict between experiment and theory is profound.

2. Mode locking - the basic process appears to be explained by electromagnetic interaction with external conductors.

3. Disruption energy quench - some of the behaviour seems to bear little relation to conventional theory.

4. The snake - its formation is perhaps understood but its persistence is unexplained.

DESTABILIZATION OF BALLOONING MODES BY SHEARED EQUILIBRIUM FLOWS IN AXISYMMETRIC PLASMAS

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In tokamaks heated by neutral beams, such as PDX and ISX-B, toroidal plasma rotation has been observed. More recently, substantial toroidal rotation of the order of the sound speed has been measured in TFTR when neutral beams are co-injected. An interesting feature of the measurements in TFTR is that the central rotation speed, after a transient phase, settles down to a steady value of $\approx (6\text{-}7) \times 10^5$m/sec in a sequence of discharges with the plasma current in the range (0.7 - 1.2)MA for which the equilibrium β lies in the range (0.26 - 0.42)%. This data is suggestive of the existence of a threshold in the rotation speed.

We develop a WKB theory for large-n ballooning modes in the presence of sheared equilibrium flows. When the flow is field-aligned, given by $\vec{v} = [\Phi(\Psi)/\rho]\vec{B}$ (where $\Phi(\Psi)$ is an arbitrary function of the poloidal flux function Ψ, ρ, the density and $\vec{B}$ the magnetic field), we show that there exists a threshold $M^2 = \beta$ (where M is the Mach number of the flow respect to the Alfven speed), just below which the plasma is unstable independent of the pressure gradient. For a typical co-injected TFTR discharge, this threshold predicts a maximum toroidal flow $\approx 8 \times 10^5$m/sec, and a maximum poloidal flow $\approx 4 \times 10^4$m/sec, which is 5% of the toroidal flow. The threshold predicted by theory for toroidal rotation is approached but never exceeded in the sequence of TFTR discharges.

For general flows, $\vec{v} = [\Phi(\Psi)/\rho]\,\vec{B} + R\Omega(\Psi)\,\hat{\phi}$, which include a purely toroidal component as well, it is shown from the WKB theory that $n \rightarrow \infty$ modes do not exist unless $\Omega(\Psi) = \Omega_0$, a constant, describing a rigid rotation. When a rigid rotation is included in the calculation, the stability threshold is unaltered. Progress towards a finite-n theory of ballooning when $d\Omega/d\Psi \neq 0$ will be reported. Based on analytical and numerical results on Suydam modes, we expect the threshold $M^2=\beta$ to occur independent of whether the shear is in the toroidal or field-aligned component of the flow.

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Thermally Driven Convective Cell Edge Turbulence: Theory and Experiment*

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Our recent theory of thermally driven convective cell edge turbulence indicates a reasonable agreement between theory and experiment as well as an explanation of some of the anomalies seen in experiment. Many tokamak experiments have incorporated edge diagnostics for the study of turbulence. One of the most extensive explorations of the plasma edge has been in progress on the TEXT tokamak[1,2]. It is well known that the highly turbulent edge consists of large potential and density fluctuations ($e\phi/T_e, n/n_o > .5$) and a correspondingly large radial particle diffusion coefficient ($D_n > 10^4 cm^2/sec$). Previous calculations have indicated a stabilyzing effect of limiters and a destabilyzing effect of impurity radiation on edge turbulence[3]. We present a unified theory of thermally driven convective cell edge turbulence which is driven by the combined effects of radiative cooling with resistivity and impurity gradients[4]. It is found that parallel thermal and impurity flows enhanced by turbulent radial diffusion saturate the thermal instability. Resultant transport coefficients and saturation levels are given for typical machine parameters. In the context of this edge turbulence theory, numerous anomalies from experiment will be discussed. Some of these include observations that potential fluctuations are significantly larger than the density fluctuations ($e\phi/T_e > n/n_o$), particle confinement time rolls over at high density, and the transport is insensitive to the loop voltage. Also, recent experimental results of impurity gas puffing experiments on TEXT will be presented and compared with the fluctuation and transport enhancement predicted by theory.

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THE FORMATION OF SUNLIKE STARS

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ABSTRACT

We describe current ideas on the formation of stars of relatively low mass (like the Sun) from large molecular clouds. We follow the process from the onset of gravitational collapse in a small dense core of a molecular cloud to the star's (and its associated nebular disk) becoming optically revealed when a powerful stellar wind clears away the surrounding obscuring gas and dust. We argue that magnetic fields coupled to lightly ionized gases play a central role in the dynamics of the first and last stages, and we outline the basic magnetohydrodynamic theories that have been developed to model the relevant mechanisms. A far-reaching consequence of the point of view adopted is that the most fundamental attribute of a star – its mass – may not be determined by the structure or dynamics of the raw material for star birth – a collapsing and rotating cloud fragment – but rather by processes that occur inside the forming star itself. This fundamental change in perspective from the older conception of a hierarchical fragmentation yields a natural explanation for why most of the known baryonic matter in the universe becomes packaged in self-gravitating balls of gas – sunlike stars – that barely have enough mass to undergo thermonuclear fusion.

NUMERICAL MHD AND PLASMA PHYSICS APPLIED TO PROBLEMS IN ASTROPHYSICS

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For Session on Space and Astrophysical Plasmas (Abstract Not Submitted)

STELLAR X-RAYS, THE SOLAR CORONA, AND SPONTANEOUS MAGNETIC DISCONTINUITIES

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Most stars emit X-rays, as thermal bremsstrahlung, indicating outer atmospheres of 10^6 K or more (> 10^2 times hotter than the stellar surface). Turning to the sun for observational guidance, it is found that the X-ray emitting regions range in size from the large active regions with scales of 2×10^5 km down to the smallest detectable "X-ray bright points" of 5×10^3 km. The X-ray emission comes from plasma of 10^{10} hydrogen atoms/ cm^3 K with surface brightness up to 10^7 ergs/cm^2 sec, essentially independent of the dimensions of the individual emitting region. The plasma is confined by bipolar magnetic fields of 10^2 gauss, in which the Alfven speed is 2×10^3 km/sec. Observations fail to detect wave motions in the X-ray emitting regions, placing upper limits of about 25 km/sec on unresolved rms fluid motions.

The heat input that creates the X-ray corona is directly related to the magnetic field, while the high electrical conductivity of the gas implies little or no resistive dissipation of the magnetic field. However, the magnetic fields are subject to continual internal winding and interweaving of their lines of force as a consequence of the random shuffling of the footpoints of the field at the photosphere. The continuous winding and interweaving causes spontaneous formation of local tangential discontinuities (current sheets) in the field, at the locations where the local magnetic pressure enhancements refract the individual lines of force to create gaps in the flux surfaces. The gaps permit initially separate field regions to come in contact, producing discontinuities where originally the field was continuous. One infers that resistive tearing instabilities etc. initiate magnetic reconnection so that the current sheets produce strong dissipation.

This phenomenon appears to be unavoidable in the solar corona. The magnetic dissipation rates are estimated to be 10^7 ergs/cm^2 sec, or larger, although the essential quantitative observations of the motions of the footpoints of the field have yet to be made. It appears, then, that each solar X-ray coronal region represents a swarm of tiny flares. Observations detect many small impulsive flare-like events in the X-ray coronal regions. The observed small flares are presumed to be the larger of the individual impulsive events, with most of them well below the observational limit of 10^{24} ergs/event.

One infers that similar swarms of small impulsive reconnection events produce the X-ray coronas of other stars like the sun, although the details lie far beyond the present observational limits.

ON THE PHYSICS OF COLLISIONLESS SHOCKS WAVES

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Collisionless shock waves are ubiquitous in most planetary and astrophysical systems. They represent strongly nonlinear plasma entities exhibiting a complex dynamic structure as a result of the interplay of microscopic and macroscopic plasma processes. Data from the multispacecraft International Space Earth Explorer (ISEE) mission combined with computer simulations using sophisticated hybrid (fluid electrons, particle ions) codes that included anomalous electron transport have produced a remarkable understanding of the earth's bow shock and of high Mach number magnetosonic shocks in general. The paper reviews first our understanding of high Mach number collisionless shock physics as applied to planetary quasi-perpendicular (i.e. magnetosonic) shocks. This is followed by a discussion of the physics of solar wind comet interactions, and the reasons that the interaction did not produce a shock structure. The paper concludes with a discussion of modern concepts concerning the structure of super-high Mach number astrophysical shocks such as occurring in supernova explosions and speculations about the structure of the so called quasi-parallel (i.e. whistler) turbulent shock waves.

IONOSPHERIC F-REGION IRREGULARITIES

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Exciting and important developments in the understanding of ionospheric F-region irregularities (i.e., electron density structure) have occurred during the past several years. Advances in computer simulation techniques, coupled with theoretical methods and up-to-date experimental data, have had a major impact in furthering this understanding. While analytical models and techniques may identify the plasma instabilities which cause these ionospheric F-region irregularities and provide estimates of saturation amplitudes, it is essential to utilize computer simulations in order to accurately model the nonlinear evolution of the unstable modes. Plasma fluid-type equations have been employed in the computer simulation models to describe ionospheric irregularity phenomena such as equatorial spread F, plasma cloud striations and high latitude structures. The recent advances in understanding these phenomena have been aided by the inclusion of ion inertia in the model equations, the use of modern nonlinear dynamics techniques, and the development of three dimensional models. This presentation will concentrate on the success story associated with equatorial spread F and the on-going research advances in high latitude F-region irregularity phenomena. Computer simulation results will be presented which highlight these successes and advancements, and will be compared to experimental observations. These studies demonstrate that ionospheric F-region irregularity phenomena can be modeled from a first principles of physics point of view.

* In collaboration with P.K. Chaturvedi, J.A. Fedder, M.J. Keskinen, H.G. Mitchell, P. Satyanarayana, and S.T. Zalesak.

Activity at Barium Clouds in Space

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As part of the Active Magnetospheric Particle Tracer Explorers (AMPTE) mission, several barium releases were carried out in the Earth's magnetotail. While *in situ* measurements by the AMPTE spacecraft indicated the formation of a diamagnetic cavity and the excitation of a broad spectrum of plasma waves, Earth based observations showed the appearance of field aligned structures, i.e. flute modes, on the surface of the expanding cloud. Similar phenomena have been observed recently at NRL in laser produced plasmas expanding into strong magnetic fields, and are probably related to the striations seen years ago in theta-pinch compressions. During the past year at least four different theoretical approaches and five different numerical simulations of this phenomena have emerged. In this talk we review this very active area of research and attempt to reconcile the various models which have been proposed.

Profile Consistency and Beta Limit Disruptions* from Resistive MHD

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We report time dependent nonlinear and quasilinear resistive MHD computations for high beta tokamaks, including a heat source and thermal conduction. We find that in a steady state, the pressure profile has a universal shape, independent of the heat source profile. Sawtooth oscillations flatten the profile, with an inversion radius proportional to the reciprocal of the safety factor at the plasma edge. Anomalous transport and profile consistency are produced by low mode number resistive modes. Mode numbers above a cutoff value are excluded from the computation, modelling finite Larmor radius effects.

If the heating rate is increased, an ideal MHD stability limit is encountered, and a disruption occurs. When this happens, the current and pressure both drop rapidly.

we have also investigated the second stable regime. Both steady states and disruptions are possible, depending on the heating rate.

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Tearing Mode Stability of the Most Probable Profile

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The axisymmetric equilibria, when perturbed arbitrarily in the poloidal flux ψ to minimize the energy $W = \int[(F^2+|\vec{\nabla}\psi|^2)/2\,R^2+P/(\gamma-1)]d\tau$ with the total current $I = \int(FF'/R+RP')\,d\tau/2\,\pi R$ as the constraint, can relax [1] to $\Delta^*\psi = -C_{\rm F}\exp(\psi/\lambda) - R^2 C_{\rm p}\exp(5\,\psi/4\,\lambda)$. The tearing mode stability [2] is studied in the cylindrical limit for the zero β plasmas governed by $\nabla^2\psi + C_{\rm F}\exp(\psi/\lambda) = 0$. It is shown that the (3,1) mode is unstable only when $q_0 > 2.0$ for typical limiter q, while the (2,1) mode is stable for $q_0 < 0.8$. Since the (1,1) mode is stable for $q_0 \geq 1.0$, the (2,1) is therefore always unstable when the (1,1) is stable. When the (2,1) is absent as q_0 falls below 0.8, the (1,1) is unstable. Implications from the present study are: (1) this most probable profile [3,4] makes (2,1) mode stability sensitive to q_0 value, and has a soft exclusion principle for (2,1) and (1,1) modes; (2) a sawtoothing tokamak plasma is likely [5] to have $q_0 < 0.8$ if the (2,1) mode is absent; and (3) the high m ($m \geq 3$) tearing modes are stable for typical q_0, q_ℓ values with this profile.

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SHERWOOD THEORY MEETING 1988

Theoretically Based Transport Models: Simulation*

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Transport coefficients predicted for drift wave turbulence, obtained by considering a different dissipative mechanism in each of four regions of velocity space [1,2], are employed together with other models to simulate TEXT discharges. The results are compared with related work on the analysis of TEXT data [3]. While drift waves and ion temperature gradient modes do yield quantitatively reasonable values of the thermal conductivity, we find that some empirical information [4] must be added to construct a transport model that yields reasonable profiles of density and temperature. In particular, the difficulty of obtaining density profiles that are consistent with measured and computed [5] ion sources is addressed. That is, an *ad hoc* inward convection must be included.

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SHERWOOD THEORY MEETING 1988

Theoretically Based Transport Models: Analysis*

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We derive approximations to the transport coefficients predicted for drift wave turbulence by considering a different dissipative mechanism in each of four regions of velocity space [1]. These are to be applied to the time dependent simulation of tokamak discharges [2], extending related work on the analysis of TEXT data [3]. We assume that the four principal drift wave types are basically the same mode, and are distinguished by the form of the electron dissipation: dissipative drift (low energy particles), collisionless or universal drift (moderate energy passing particles), dissipative trapped electron (moderate energy trapped particles), and collisionless trapped electron (high energy trapped particles). We obtain analytical formulas for the particle and thermal fluxes in the form $\Gamma = - D\partial n_e/\partial r - D_T\partial T_e/\partial r$, and $q_e = - \chi_{en}\partial n_e/\partial r - \chi_e\partial T_e/\partial r$ [4]. In principle, either flux can change sign, depending on the values of $\eta_e = \partial \ln T_e/\partial \ln n_e$ and the boundaries in velocity space, v/v_{the}, of the four contributions. In practice, it is difficult to produce an inward particle flux (and even more difficult to produce an inward heat pinch). Thus, there is a problem to be faced in attempting to use the full quasilinear expressions self-consistently. Further, we suggest that the contribution from the dissipative trapped electron terms is smaller than usually asserted. Similar results will be obtained for the particle and electron thermal fluxes driven by the ion temperature gradient modes [5].

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SHERWOOD THEORY MEETING 1988

The Empirical Tokamak: Confidence Limits on Estimated Model Parameters*

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A comprehensive comparison between theory and experiment via predictive transport simulation requires complete sets of experimental data covering the entire operating regime of the tokamak. In order to construct the complete data sets necessary for this comparison it is necessary to find some way to aggregate experimental results from a variety of diagnostics into useful data sets. One way to accomplish this aggregation is to generate a model for each diagnostic.

In this approach, all the available data for a given diagnostic is used to obtain an empirical fit to the data covering the entire operating regime of the device. For example, given the data,

$$Te(r_i,Bt_j,Ip_j,ne_j,...) = xxx\ kV$$

construct a fit,

$$Te(r,Bt,Ip,ne,...) = F(r,a,b,c...).$$

where a, b, c, etc. are the parameters which determine the fit and which are functions of the discharge parameters, i. e., a = a(Bt,Ip,ne,...). Therefore, for any set of discharge conditions a value of the electron temperature can be obtained by evaluating the fit function F. It is the computation of this function and its confidence limits which is the focus of this paper.

The construction of F consists of two parts. First determine the general functional form to be used, e. g., linear, parabola to a power, exponential, etc. Next find the parameters in the fit via minimizing χ^2 or using *M-estimates* [1]. Contours of constant $\Delta\chi^2$ are then computed and associated with confidence levels using a Monte Carlo simulation of synthetic data sets. A description of the algorithms used and specific applications to TEXT will be given.

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SHERWOOD THEORY MEETING 1988

Destabilization of the Toroidal Discrete Shear Alfvén Wave by Alpha Particles in an Ignited Tokamak *

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It is known that both the global Alfvén wave and the kinetic Alfvén wave can be destabilized through wave-particle resonant interaction with highly energetic particles whose parallel motion is super-Alfvénic, e.g., fusion-product alpha particles in an ignited plasma.[1–3] Here, we consolidate our previous results[4–6] concerning destabilization of Alfvén waves by alpha particles and also present new results about kinetic effects on the toroidicity-induced discrete shear Alfvén gap mode.

We primarily consider the global shear Alfvén wave, instead of the kinetic Alfvén wave, since the results in Ref. 3 indicate that the global modes are more persistently unstable than the localized kinetic Alfvén wave. There are two types of global Alfvén modes in a tokamak: one type, called the cylindrical global Alfvén eigenmode (CGAE), exists in cylindrical geometry, with its frequency just below the minimum of the Alfvén continuum; the other type, called the toroidal Alfvén gap eigenmode (TAGE), is characterized by having its frequency lie within toroidicity-induced gaps in the Alfvén continuum.[7]

Previously the following results had been found:

1. The growth rate of the cylindrical GAE is significantly enhanced when a slowing-down distribution is used to model the alpha particles, as opposed to a Maxwellian. For example, with the parameters of the proposed Compact Ignition Tokamak (CIT) device and for the expected alpha particle birth distribution, the CGAE is found to be unstable.[4,5] The same conclusion is also obtained for the parameters of the proposed ITER device.[8]
2. The effect of toroidicity on the CGAE is to induce coupling to sidebands, which tends to stabilize this mode, as long as one of the sidebands has a shear Alfvén resonance[6]; if not, the most unstable CGAE, usually the ($n = 0$, $m = -2$) mode, remains unstable. These toroidal effects are somewhat sensitive to the details of the toroidal shear Alfvén continuum — in particular, the plasma edge conditions — and therefore an extended study with realistic tokamak equilibria is required for an accurate assessment.
3. The TAGE is also destabilized by alpha particles.[4,5] In fact, the growth rate of the TAGE is typically one order of magnitude larger than that of the CGAE.

More recently, we have studied whether kinetic effects will modify this unstable behavior of the TAGE. For CIT parameters, we find both analytically and numerically that kinetic effects are negligibly small for this mode. Landau damping on the TAGE is about two orders of magnitude smaller than the alpha particle-induced growth rate and hence can be neglected, as in Ref. 4.

We conclude that this toroidal Alfvén gap eigenmode appears to be important for the confinement of alpha particles in an ignited tokamak device and therefore deserves increased theoretical, as well as experimental, investigation.

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A Finite-Banana-Width, Bounce-Averaged, Fokker-Planck Operator for Tokamaks–Applications to Neoclassical Transport Theory. *

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The Fokker-Planck operator is represented in a coordinate system based on the Constants of Motion (COMs) v_0, θ_0, $\bar{\Psi}$. The nearly recurrent motion inherent in tokamak systems is phase-averaged to produce an operator which describes the time evolution of the particle distribution in this COM space. The use of finite-banana-width orbits in defining the COM system leads naturally to an operator which includes transport processes.

In order to develop a transport theory, the operator is separated by orders of the small parameter ρ_p/a, the ratio of the poloidal gyroradius to the minor radius. Transport equations are then produced by taking simple moments of the second-order equation. The resulting transport coefficients are compared to standard neoclassical transport coefficients in the appropriate limit. A key feature of the theory is that it makes no assumption as to the smallness of the inverse aspect ratio.

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New Features of the NMFECC Fokker-Planck Facility CQL(02) *

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A second version of **CQL**, the bounce-averaged Fokker-Planck code facility under development at NMFECC, is now available to the user community. The update features a number of improvements which enhance efficiency while expanding the range of physical effects considered. (1) The steady state engine runs nearly an order of magnitude faster than previously, allowing for the matrix inversion of a 100 X 100 mesh resolution case in about .6 seconds on the CRAY-2. (2) Dynamic memory management is used in several contexts to allow solutions on refined meshes while optimizing the balance of CPU and memory charges. (3) A "sweep" option has been installed which allows the user to specify an input variable by name with respect to which a parameter sweep is desired. The sweep is performed and results are displayed graphically. (4) A highly flexible resonance broadening model has been included in the RF module which allows the computation of trajectory integrals to occur prior to run time. For the user who simply copies the data base along with the source the implementation cost is insignificant. (5) Time evolution and RF physics computations take place on independently structured meshes, allowing increased resolution where necessary at no extra cost. (6) A 3-D finite banana width collision operator has been implemented as a cooperative module of **CQL**. Neoclassical radial fluxes based on any of the thermodynamic drives can be computed. (Details are presented in another poster by G.Tomaschke) (7) Extensive graphics capabilty and control improvements have been made allowing the user to tailor the form of the output to his own taste.

CQL was designed for NMFECC users as a physics utility. It has been our intention to address as broad a spectrum of computational needs of the fusion community as possible. We have tried to incorporate in a consistent framework several diverse phenomena which could occur in an experiment in order to evaluate their relative importance. Options available in the use of the code will be demonstrated and examples of various physics parameter studies of current interest will be presented.

It is our intention that by providing a focus for the creation, maintenance, and development of a multi-purpose physics facility such as **CQL** we may allow collaborative research on a scale which would otherwise be difficult to coordinate. We invite comments, suggestions and participation from all interested in using or developing this facility.

* Work performed under the auspices of the U.S.D.O.E. by LLNL under contract No. W-7405-ENG-48.

Developments in the Theory of Ion Temperature Gradient Turbulence in Tokamaks

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The theory of ion temperature gradient driven turbulence is extended to two comparatively unexplored regimes. First is the case of a flat ion density profile ($L_n \to \infty$), which may occur in H-mode discharges. An improved 'mixing length' theory, in which the thermal diffusivity is determined from the condition of saturation, has been used to determine ion and electron thermal transport coefficients for the 'slab-like' ∇T_i-driven mode. The effects of higher radial eigenmodes have been included. Results indicate that that transport is <u>not</u> dramatically reduced in flat-density regimes, thus calling into question various schemes for explaining the enhanced confinement of H-mode plasmas.

The second topic of study is the development of a theory of η_i-driven turbulence near the instability threshold. Weak turbulence theory is used to construct a wave kinetic equation (WKE), starting from the nonlinear gyrokinetic equation. The WKE is then used to assess the effects of various nonlinear wave-wave and wave-particle interaction processes. Results will be discussed.

SHERWOOD THEORY MEETING 1988

The High Frequency Hot Electron Interchange Mode in a Cylindrical Hollow Pure Hot Electron Plasma*

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In order to understand the quiescent behavior of a hollow pure hot electron plasma in the baseball mirror, Constance-B, we investigate the high frequency hot electron interchange mode in a shearless cylindrical model. A shooting code is set up for the second order differential eigenmode equation in connection with the parameters of Constance-B. A flute-like interchange mode, localized in the hollow region, has been found unstable in the MHD limit, which can be viewed as an extremely low density limit, so that the kinetic effects from hot electrons are suppressed. The numerical results, which take the above results as an initial guess, will be presented for the density in Constance-B. The kinetic effects due to hot electrons are important for experimental parameters.

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AEL 32:22 2/29/88

Fokker-Planck Simulation of a Migma Reactor

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A two-dimensional multispecies nonlinear Fokker-Planck numerical simulation of a D^3He fueled aneutronic (neutron power $\leq$ 4% reactor power) migma reactor is used to investigate the dependency of Q (power output / power input) on important plasma parameters. The migma orbits[1] have large Larmor radii, which create a diamagnetic well at high densities, thus suppressing synchrotron radiation losses. FPPAC[2] is used as the core of the energy balance simulation that incorporates radiative effects as well as primary and secondary nuclear reaction chains. The plasma parameters varied are the end plug potential, the mirror ratio, the ion injection energies, and fuel ratios.

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**Supported by USAF Contract F29601-87-C-0064.

[1] D AlSalameh, et al, Phys. Rev Lett. 54 (1985) 796-799.

[2] M.G McCoy, A.A Mirin, and J. Killeen. Computational Comm. 24 (1981) 37-61.

TRANSPORT AND STABILITY OF Z PINCH FIBERS

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Previous work has shown that time and space separable solutions exist for the z-pinch transport equations and that these solutions are attractors.[1] This work has been extended to electric field specified boundary conditions (rather than current specified) which are more compatible with the experimental case. A new class of separable solutions have now been found for the constant voltage case. These results will be presented.

Previous stability work indicated that stabilization of $m = 0$ modes through dissipation was possible, provided that the current density could be confined to the edge.[2] This work has been extended to include the full Braginskii ion stress tensor, hall effects, diamagnetic effects, and finite density gradients. Results will be presented.

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[b] Department of Mechanical Engineering, Technion, Israel Institute of Technology, Haifa 32000, Israel.

[1] P. Rosenau, R. A. Nebel, and H. R. Lewis, "Analysis of Plasma Transport with Application to Z-Pinch Fibers," Los Alamos National Laboratory report LA-UR-87-3319, (submitted to Physics of Fluids for publication).

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Sherwood Theory Conference
Gatlinburg, Tennessee
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RFP Behavior with a Resistive Wall*

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It is hoped that RFP experiments can be operated with a resistive wall, in order to allow for active equilibrium position control with a vertical field. MHD computation (using reduced MHD) indicates possible difficulties with this approach. The usual m=1 internal kinks which produce the dynamo, penetrate the wall, in a characteristic time, and grow to larger amplitude. The reversal parameter F becomes much more negative, indicating that a larger electric field is required to maintain the current or θ at a constant value. The resistive wall also tends to produce a less turbulent steady state, but with large amplitude magnetic perturbations.

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SHERWOOD THEORY MEETING 1988

Study of the current sheet in a field reversed configuration*

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A test particle code is used to investigate the dynamics of charged particles in a field reversed layer described by $B_x = B_0 \tanh(z/a)$. A magnetic tearing perturbation and a normal magnetic field component $B_z = \mathrm{B}_0\psi_0 k\cos(kx)e^{\gamma t} + B_0 b$ are added to the reversed field. Electrons and ions are treated separatedly and a realistic mass ratio of 1836 is used. The number of particles in the simulation varies from 32000 to 64000 and the system is advanced for 200–300 cyclotron periods $2\pi/\omega_{cs}$. The magnitude of the current layer is determined as a function of the normal field strength b and the perturbation amplitude ψ_0, and it is found to increase linearly with ψ_0 for $\psi_0 k \ll 1$. For larger values of $\psi_0 k$ the current increases slower with ψ_0, and there is evidence of saturation for $\psi_0 k \simeq 1$. The width Δz of the layer is found to be given by $\Delta z = \sqrt{a\rho_s}$, where ρ_s is the cyclotron radius of the particles of species s, within the error of the calculation, typically 5%. The current is also found to be confined in the y-direction within a layer whose width and position depends on the ratio ψ_0/b. The height-integrated in-phase part of the perturbed current $\langle j.E\rangle$, which is a measure of the power transfer from the field to the particles, is also computed and used to estimate the reconnection growth rate.

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Magnetic Surface Destruction by Ion Cyclotron Frequency Radiation

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It is well known that magnetic islands and ergodic magnetic force lines are intrinsic to fully asymmetric, toroidal, plasma configurations. Asymmetry typically arises from the geometry of the containment device. Another possible form of asymmetry, one that has received little attention in the past, is that produced by electric and magnetic fields of rf waves in the plasma. Such fields can react on equilibrium states of plasma, producing an effective quasi-static force that breaks spatial symmetry, thereby altering plasma properties. In this communication, we explore the effects of wave induced asymmetries on the topology of equilibrium magnetic surfaces. Our analysis is carried out in the ion cyclotron range of frequencies (ICRF). Starting with a toroidal plasma configuration that has well-defined, nested magnetic surfaces, we introduce a spectrum of ICRF waves that perturb the underlying equilibrium geometry. The perturbed plasma equilibrium is governed by a modified form of the familiar equations of ideal magnetohydrodynamics. The wave fields give rise to a spatially dependent force, $\mathbf{F}_{rf}(\mathbf{r})$, that must be included in the macroscopic force balance equation, producing the relation, $\mathbf{J} \times \mathbf{B} = \nabla P + \mathbf{F}_{rf}$, where $\mathbf{J}$, $\mathbf{B}$ and P designate, respectively, the equilibrium current density, magnetic field and pressure. The modified force balance equation, coupled with Ampère's law, $\nabla \times \mathbf{B} = \mathbf{J}$, and the constraint, $\nabla \cdot \mathbf{B} = 0$, determine the properties of the equilibrium magnetic surfaces, $\psi(\mathbf{r})$ = const., where $\psi(\mathbf{r})$ satisfies, $\mathbf{B} \cdot \nabla \psi = 0$. We explore the topology of magnetic surfaces via a perturbation analysis of the magnetic force line equations expressed as a Hamiltonian system. We assume two small parameters, the plasma pressure and the strength of the induced rf force. To lowest order in these parameters, the configuration has nested vacuum magnetic surfaces, free of island structures. Plasma pressure and the rf force perturb these surfaces, producing magnetic islands about rational magnetic surfaces of the vacuum magnetic field. The width of the islands, as well as properties of the plasma in the island region, are identified by introducing appropriate canonical transformations in the governing Hamiltonian system. A nonlinear partial differential equation, which is a nonlinear variant of the familiar Grad-Shafranov equation, emerges as the governing equation of the island region. Our analysis reveals that the pressure and rf force are competitive mechanisms for creation of magnetic islands. As rf intensity increases, islands grow and eventually overlap. Particle diffusion may then result. A preliminary estimate reveals that an rf magnetic field of order fifty Gauss can produce diffusion at a rate comparable to that observed in present Tokamak experiments. Fluctuating magnetic fields of this order can be expected in the near field of rf antennas.

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PROPERTIES OF η_i-INSTABILITIES IN H-MODE PLASMAS*

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Experimental results from tokamaks such as DIII-D have indicated that the electron density profile in H-mode discharges can be nearly flat over most of the plasma and, in some cases, even inverted. These conditions have very interesting implications for η_i-mode-based thermal transport models. Specifically, very large and/or negative values of the parameter, $\eta_i \equiv d\ln T_i/d\ln n_i$, now characterize these discharges which nevertheless exhibit favorable confinement properties. This has motivated the present systematic analysis of threshold criteria for η_i-modes in plasmas with normal, flat, and inverted density profiles. Analytic and numerical calculations are carried out for a sheared slab geometry with resonant particle effects taken into account. The principal results are (i) the familiar criterion, $1 < \eta_{ic} < 2$ (with $\eta_i > \eta_{ic}$ for instability) holds only when $0 < L_n/L_s << 1$; (ii) in the weak density gradient limit, $|L_n/L_s| \gtrsim 1$, the threshold becomes independent of L_n (with L_n and L_s being the density and shear scale lengths), i.e., $\eta_{ic} \simeq 1.9 \times (1+T_i/T_e)L_n/L_s$; and (iii) for inverted gradients ($\eta_i < 0$), instability can occur when $\eta_i < \eta_{ic} \lesssim -1$ with the magnitude of η_{ic}^- increasing with T_e/T_i. Typical H-mode profiles of n_e, Z_{eff}, and T_e from DIII-D suggest values of η_i which are not very far from the thresholds calculated for cases (ii) and (iii). Furthermore, recent nonlinear studies[1] show that χ_i (ion thermal diffusivity) becomes independent of L_n (rather than increases with L_n) and is only weakly dependent on L_s when $|Re(\omega)| \geq \gamma_{linear}$. This is also consistent with the improved thermal transport observed in H-mode plasmas with nearly flat density profiles.

[1]T.S. Hahm et al.; R.D. Sydora, et al., papers presented at this meeting.

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Nonlinear Evolution of Ion Temperature Gradient Driven Instabilities and the Associated Thermal Transport*

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Nonlinear gyrokinetic equations in sheared slab geometry have been used for the investigation of the saturation of η_i-instabilities and the associated ion thermal transport. Based on the renormalized nonlinear mode coupling theory, in which the real frequency for the radial eigenmode is taken to be finite, i.e., $|Re(\omega)| \gtrsim \gamma$, we have found that the saturation level of the fluctuations and the corresponding ion thermal diffusivity are independent of the density scale length L_n and are weakly dependent on the shear scale length L_s. These predictions are in broad agreement with the results from the gyrokinetic particle simulation, which has been carried out in three-dimensional geometry with multiple rational surfaces.[1] We have also studied the conservation properties of the gyrokinetic equations in an effort to determine the roles played by the ion Landau damping and the electron dissipation for the steady-state thermal transport. To account for the effects of electron-ion collisions, a special numerical scheme based on the linearized gyrokinetic particle simulation model[2] has been developed. Finally, the scaling laws for the saturation amplitude and the resulting thermal transport based on the invariance properties of the gyrokinetic system and their comparisons with the simulation results and the theoretical predictions will also be presented.

*This work is supported by DoE Contract #DE-AC02-76-CHO-3073.

[1]R. D. Sydora, W. W. Lee, T. S. Hahm, and J. M. Dawson, this conference.
[2]A. M. Dimits and W. W. Lee, 12th Conference on Numerical Simulation of Plasmas, San Francisco (Sept. 1987).

BETAS, a spectral code for three dimensional Magnetohydrodynamic Equilibrium and Nonlinear Stability calculations.

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Abstract: A fully three dimensional spectral code has been developed and implemented. It computes three dimensional equilibria using the variational approach, by minimizing the potential energy subject to appropriate constraints. A second minimization, with an additional constraint, is used to examine the stability of solutions.

The magnetic field representation allows for non-nested flux surfaces. Thus it can be used to study solutions with islands and variation of the potential energy with respect to topology changes.

A spectral representation in the toroidal and poloidal angles, coupled with a special choice of collocation points in the radial direction results in greatly enhanced resolution.

A fast iterative method was developed , with the number of iterations required for convergence independent of the mesh size. Residuals converge exponentially to the round-off error, allowing the potential energy to be computed to the eight digit accuracy required for nonlinear stability analysis. A small amount of artificial viscosity may be needed for convergence in cases where low order resonances are present in the plasma region.

Numerical results show convergence to known axially symmetric equilibrium solutions, as well as close agreement with eigenvalue calculations in helically symmetric stellarator configurations. Solutions exhibiting island formations are found to have lower potential energy than that of the nearby nested case. Internal modes are found to localize inside the resonant surface, with the eigenfunction having sharp gradients at the resonant surface.

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Simulation of Beam Driven Currents in Tokamaks*

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A computational model for beam-driven tokamak currents has been developed for use in a time dependent 1-1/2 D transport code. The calculation is based on work by Hirshman and Sigmar.[1] The model incorporates a steady state estimate of the pitch angle scattering of beam ions, as well as the friction against thermal species. A pencil beam model is used to define the birth points on the flux surfaces, which are defined by a moments method solution of the 2-D equilibrium. The current drive mechanism is accompanied by heating, so that both the pressure and current density are directly affected; these in turn modify the MHD equilibrium. Self-consistency is obtained by alternately calculating the driven current, the MHD equilibrium, and the plasma transport as the system evolves in time. A simple ballooning mode stability criterion is used, and a "generic" current source profile is added to the beam-driven portion in order to improve the stability. Typical current profiles and the operating window in the density temperature plane are shown for an ITER configuration.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

[1] S. P.Hirshman and D. J.Sigmar, Nucl. Fus. **21**, 1079(1981)

RADIAL PARTICLE FLUXES AND THE BOOTSTRAP CURRENT IN AN ATF-LIKE STELLARATOR REACTOR

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ABSTRACT

We present results from the code FLOCS (Flow Code For Stellarators), which computes the self-consistent radial particle fluxes and the bootstrap current in stellarators. The results are for a stellarator reactor plasma extrapolated from ATF parameters.

The computer code finds the distribution function as a function of three variables, one spatial, θ, and two in velocity space, E and k^2 where k^2 is the ripple depth parameter. f is computed on a fixed flux surface, and bounce-averaging over the helical ripples effectively eliminates the toroidal angle from the problem. The energy integrated particle fluxes are computed, and the balance point where ion and electron fluxes are equal determines the electric field. To perform the integrations over energy as well as to include the momentum restoring terms, a multi-mesh method in k^2 is employed.

The bootstrap current is also evaluated from $\bar{f}$. Although $\langle J_{\parallel} B \rangle$ is related to the variation of f along a field line, $\partial f/\partial \ell$, we show that $\partial \bar{f}/\partial \ell_{av} \gg \partial \tilde{f}/\partial \ell$ and argue that the important drag exerted by helically trapped particles on toroidally blocked and passing particles is properly included. It is one of the goals of this research to investigate the impact of momentum restoring terms in the collision operator, C. Theoretically, their presence is required to "replace" the parallel momentum that is lost by the Lorentz part of C.

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TOROIDAL ION-PRESSURE-GRADIENT-DRIVEN DRIFT INSTABILITIES AND TRANSPORT REVISITED

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A unified theory of ion-pressure-gradient-driven drift wave instabilities and transport is presented which ties the long-wavelength trapped-ion mode to the moderate-wavelength hydrodynamic mode in toroidal geometry. A general dispersion relation, together with expressions for the eigenfrequencies and eigenwidths, are derived from kinetic theory for both cases. The stabilizing influence of perpendicular compression, as well as the flat and inverted density profile limits, are explored. Such situations are all of potential relevance to H-mode discharges. Mixing-length expressions for the fluctuation amplitudes and transport coefficients are derived. It is further shown that a population of energetic trapped particles, such as those that may be produced during radio-frequency or perpendicular neutral beam heating, can significantly exacerbate the instability. Several suggestions for experiments are made to help in differentiating among various anomalous transport scenarios.

Effect of Temperature Gradients on Dissipative Trapped Ion Mode

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We find that for $\eta_i > 4/3$ ion dissipation destabilizes the trapped ion mode with frequency $\omega \sim \omega_* \varepsilon^{-1/2}$. For further $\eta_i > \varepsilon^{-1/2}$ and $\nu_{eff} < \omega$ the mode becomes purely growing with $\gamma \sim (\omega_{*T} \overline{\omega}_d)^{1/2}$. Using a mixing-length estimate for the diffusion coefficient, the ion thermal diffusion scales as $(k_\theta \rho_s)^{-1}$ If $\nu_{eff} < \omega$ determines the maximum growing wavelength we find

$$\chi_i \sim \frac{\varepsilon^{5/4}}{\hat{s}^2 \nu_{ii}} \frac{\rho_s^2 \, c_s^2}{L_{Ti} \, R}$$

Such rapid transport further strengthens the argument that the maximum η_i will be determined by the requirement of proximity to marginal stability.[1,2]

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2. H. Biglari et al., *Phys. Rev. Lett.* **60** 200 (1987).

On the Theoretical Foundations of the Troyon-Sykes Scaling*

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The optimum tokamak beta values compatible with ideal MHD stability against both low-n and high-n pressure driven modes in the first stability regime have been found to obey the Troyon-Sykes formula[1,2]: $\beta_{opt} = C\ I/aB$. However, despite its simplicity and universality, the nature of this scaling law remains empirical to date. A better theoretical understanding of the Troyon-Sykes scaling can be achieved by considering the finite-beta equilibrium model of Clarke and Sigmar[3]. Using this model it is shown that, for configurations with vanishing current density at the plasma edge, the ratio $\beta aB/I$ must have an upper bound as a result of equilibrium constraints only. Conversely, the "alternate" ratio $\beta a^2 B^2/I^2 \sim \beta_p$ is unbounded. This provides a good reason for the appropriateness of the Troyon-Sykes scaling law as well as its universality. In addition it is shown that the optimum value of $\beta aB/I$ should depend on q_o and scale like q_o^{-1}.

By considering the stability against high-n ballooning modes in the above model, an optimized β is obtained as a function of I/aB. To a very good approximation and for nearly the full range of permissible equilibrium values of I/aB (well beyond the external kink stability limit) the relation between $\beta_{opt}(n = \infty)$ and I/aB is linear. The numerical value of the corresponding slope coincides with that of the Troyon-Sykes constant C.

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2. A. Sykes et al., in Proc. 11th European Conf., Aachen 1983, Vol. 2 p. 363.
3. J. F. Clarke and D. J. Sigmar, Phys. Rev. Lett. **38**,70 (1977).

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Three Dimensional Gyrokinetic Particle Simulation Model for Studying Low Frequency Fluctuations in Tokamaks*

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A three dimensional gyrokinetic plasma simulation model in cylindrical geometry has been developed for the purpose of investigating kinetic effects on low frequency global modes such as interchange and ideal kink instabilities. The model, which includes plasma inhomogeneity and rotational transform, is based on the gyrophase-averaged Vlasov and Poisson equations in toroidal geometry.[1,2] Briefly, the particle (electron and ion) motion is represented by the E×B drift in the direction perpendicular to the ambient magnetic field and by the full dynamics in the parallel direction, whereas the effect of ion polarization drift is accounted for in the gyrokinetic Poisson equation. In addition, electron-ion collisions are introduced by using a pitch angle Monte Carlo scattering method. The thermal equilibrium fluctuation spectrum and the numerical properties for such a system in comparison with theoretically predicted values have been studied in detail with satisfactory results. The investigation of the linear growths and saturation of interchange and drift-interchange modes based on the initial electrostatic version of the code has been carried out. The simulation results with magnetic shear reveal the presence of several unstable long wavelength interchange modes which saturate through pressure mixing over the width of the eigenmode. The growth rates, real frequencies and radial mode structures observed in the simulation agree quite well with the linear stability analysis. The saturation levels for the density and the electrostatic potential also compare favorably with the estimates based on the mixing length argument. The inclusion of the inductive parallel electric field in the equations of motion has recently been made. These results along with those for using beam ion distributions to examine the influence of energetic ions on the stability of interchange modes will be presented.

*This work is supported by the DoE Contract #DE-FG03-86ER53225

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[1]W. W. Lee, Phys. Fluids, 26, 556 (1983).
[2]T. S. Hahm, Princeton Plasma Physics Laboratory Report PPPL-2513 (1988).

Fueling and Current Drive with Compact Toroids in a Steady-State Tokamak Reactor*

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It has been suggested that a tokamak reactor might be maintained in steady-state operation by periodically injecting compact toroids (CTs) to both provide fuel and increase the helicity, thereby maintaining the plasma current.[1] In this paper we examine such reactor scenarios using a model suggested by Parks,[2] in which the CT slows down by the emission of an Alfvén wake. We look for scenarios which minimize the power requirements for fueling alone, or fueling together with current drive. We consider several constraints, including MHD beta limits for the CT (taken to be about 20%), three-body recombination of the dense cold plasma within the CT, ejection of the CT from the tokamak by ∇B forces before reconnection occurs, and the maximum credible repetition rate of a CT gun (taken to be about 1 kHz). We conclude that the power required for a CT fueling system is minimized by rapidly injecting many small, dense CTs at relatively low velocities, $V_{CT}/V_A \sim 10^{-2}$. Such a fueling system would require less than 1% of the power required for heating the tokamak (or the alpha particle power for an ignited reactor). A system that both fuels and drives all of the plasma current requires somewhat more power. However, it appears that a steady-state reactor with a Q as high as 60 might be possible using CT injection.

* This work was 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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SHERWOOD THEORY MEETING 1988

Investigations of Nonlinear Semicollisional Magnetic Islands in a Torus*

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Semicollisional drift tearing modes become nonlinear when their island width exceeds the linear layer width (as found in previous nonlinear investigations[1]). In a torus, they can remain semicollisional for island widths up to a poloidal gyroradius. Realistic levels of coil error fields produce magnetic islands in this range. We find that island dynamics and stability in the nonlinear regime depends on parameters other than Δ': bootstrap currents, global radial electric fields, particle diffusion, and external error fields play important roles. Some of these effects are described here analytically in various limits. Also, a particle code is under development to investigate semicollisional modes, for single and multiple helicity, which includes the effects above.

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

CALCULATION OF NEUTRAL BEAM CURRENT DRIVE IN THE PRESENCE OF ALFVÉN WAVE TURBULENCE [1]

Robert B. Campbell (TRW/LLNL)

I have developed a two-dimensional quasilinear code in order to assess the degradation of neutral beam current drive efficiency due to turbulence excited by the injection of super-Alfvénic particles. My code uses Kennel-Englemann quasilinear theory for the compressional and shear Alfvén waves. The beam distribution function has been expanded in Legendre polynomials, resulting in a set of coupled ODE's in the speed coordinate. I have calculated growth rates of the modes using the collisional distribution, and I obtain the relaxed distribution for a given turbulence level. I obtain the self-consistent turbulence level by balancing the mode growth from beam particles and the mode damping from electrons and alpha particles. I will present quantitative results for the reduction in current drive efficiency. Below I show a typical distribution function in normalized perpendicular and parallel velocity components:

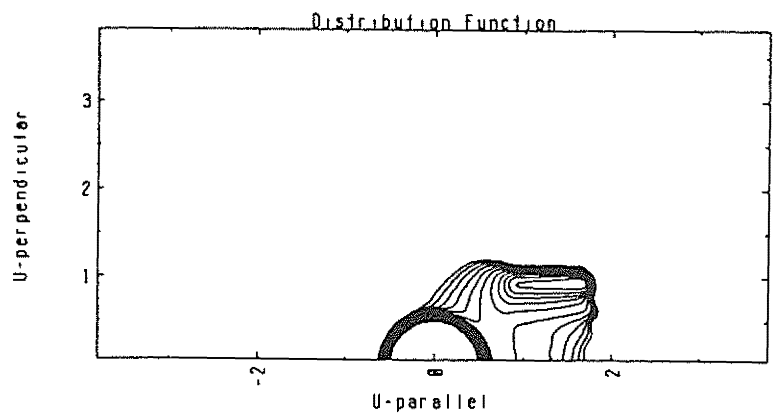

Figure 1: Beam Heated Distribution Modified by Compressional Mode Turbulence.

[1]Work performed under the auspices of the USDOE by LLNL under contract W-7405-ENG-48 and TRW subcontract number 2375703.

EXPLICIT EVALUATION OF THE GENERALIZED BALESCU-LENARD COLLISION OPERATOR*

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In previous work[1], the Balescu-Lenard (BL) collision operator was generalized to an operator acting on the space $\mathcal{J}$ of invariant momenta of the unperturbed particle motion. The same "generalized BL" (gBL) operator thus applies, with appropriate specialization of the actions $\mathcal{J}$, to any configuration having integrable unperturbed motion, including tokamaks, for which the specialization is $\mathcal{J} = (\mu, J_b, p_\zeta)$, with the diffusion and drag in the toroidal angular momentum p_ζ corresponding to radial transport. While some significant implications for tokamak transport could be drawn from the properties of the formal gBL operator, for more precise statements an explicit evaluation of the form is necessary. It has proven possible to carry out this explicit (thought approximate) evaluation of the operator for arbitrary mass ratio M_1/M_2 of the scattered to scattering species, and for each of the three tokamak transport mechanisms [symmetric (neoclassical), turbulent, and ripple], which appear within the gBL operator as simply specializations of the same general form to differing perturbation wavelength ranges.

As for the standard operator, the gBL operator is the sum of a diffusive term and a dynamic friction term $\mathcal{F}$. Evaluating the diffusive portion yields test-particle banana diffusion for the symmetric collisional spectrum, a generalization of the Rechester-Rosenbluth formula for the magnetic turbulent spectrum, and a generalization of the 'stochastic regime' of Goldston, White, and Boozer for ripple perturbations. As expected from the formal operator, including self-consistency effects by evaluating $\mathcal{F}$ for both the collisional and turbulent spectra yields a closely-related pinch term, necessary for maintenance of P_ζ-conservation, making the resulting particle fluxes intrinsically ambipolar, and thus substantially reducing the particle flux for the species expected to escape more rapidly from the test-particle calculation alone (ions for the symmetric case, electrons for the case of magnetic turbulence).

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2C29

FAST CURRENT PENETRATION IN EXPANDING TOKAMAKS*

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Simulations of the toroidal current evolution in large tokamaks such as TFTR and PBX are found to be in good agreement with experimental results. However, in CIT, the plasma current is required to ramp much faster, from 0 to 9.0 MA in 6 seconds. To avoid the formation of MHD unstable hollow current profiles during the current ramp phase, an unconventional mode of operation for CIT is proposed where the toroidal flux domain of the CIT plasma expands due to a combination of changing major radius, cross sectional shaping, and toroidal field ramping. Simulations show that stable profiles can be maintained during the entire CIT discharge using these techniques. Approximate analytic models give insight into the fast current ramp technique and provide scaling relations which agree well with simulation results.

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RESISTIVE FLUID TURBULENCE INDUCED TRANSPORT AND RADIAL ELECTRIC FIELD*

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Recently, transport theory of low-frequency ($\omega < \omega_{ci}$) fluctuations in toroidal plasma has been reformulated by using quasilinear neoclassical theory.[1] The results of this investigation have shown that particle and heat fluxes depend explicitly on the radial electric field E_r, and the fluctuation amplitudes. With experimental indication of the influence of radial electric fields on the particle confinement in the neutral-beam-heated ISX-B tokamak experiment,[2] it has been suggested that changes in the fluctuation-induced transport flux due to changes in the electric field account for the L-H transition and density clamping phenomena.

Here we present a theory of saturated resistive fluid turbulence with the influence of radial electric fields as a possible dynamical mechanism explaining the experimental observations. In particular, two cases of resistivity-gradient-driven turbulence with opposite signs of the radial electric field will be presented as a possible explanation of different regimes of tokamak edge phenomena.

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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Nonlinear MHD Simulation of an RFP with Nonideal Boundary Conditions*

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Currently, it is unknown whether an RFP will operate with a relatively short timescale shell as required for long pulse length experiments. Thus. we use a 3D MHD code to study a reversed-field-pinch with a thin resistive shell and an outer conducting wall. The initial equilibrium and fluctuation spectrum is generally obtained by running the code with a close-fittting outer wall until a steady state sustained by "dynamo" is reached. The conducting wall is then placed at an arbitrary radius for subsequent runs.

Constant pinch parameter (Θ) simulations exhibit rising loop voltage V_L with increasing vacuum thickness due largely to greater m=1 "dynamo" activity. At Θ=1.73, V_L increased ~ 50% with the conducting wall radius only 5% larger then the minor radius of the plasma. At Θ=1.59, the rise in V_L is less dramatic, at ~35% with 15% vacuum. These results indicate that simple MHD activity can account for at least part of the anomalous V_L seen in RFP experiments with limiters[1]. A quasi-steady RFP state is found with up to 60% vacuum (larger vacuum region cases are being investigated) at Θ=1.59, albeit with 3 times larger V_L and 2 orders of magnitude increase in fluctuation kinetic energy.

Constant V_L simulations for which the conducting wall is removed have been performed for shell time τ_S=0 1 ($\tau_S=\Delta\eta/a\eta_S$ in units of plasma resistive diffusion time, where Δ=shell thickness, η and η_S are plasma and shell resistivity respectively). Reversal of the toroidal magnetic field is lost in less then one shell time as the plasma evolved toward a tokamak-like state. In general, m=1, n<0 "dynamo" modes exhibit far greater dependence on boundary condition then predicted by linear stability analysis. This may be due to quasi-linear interaction with m=0 modes which can be prominent at moderate vacuum thickness with sufficient reversal. The m=1, n>0 external kinks are not seen to play an important role, in contrast to earlier simulations without resistive diffusion of the m=0, n=0 component of the equilibrium (no "dynamo" needed).

*Work supported by U.S.D.O.E.
**Address: SAIC at San Diego
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COUPLING THEORY OF RF WAVES WITH RESONANT LOOP ANTENNAS IN TOKAMAKS*

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We are developing a computation method to study the coupling theory of resonant loop antennas with rf waves in tokamak. The E-field in an antenna-vacuum system is obtained from the scalar potential Φ and the vector potential, Ay, by solving the Laplace equation in 2-D approximation using the SOR convergent schemes.[1] Including finite Larmor radius and finite electron inertial mass effects, the wave equations in plasma are also solved by using the finite element method[2] for the perturbed E fields in a long cylindrical plasma boundary. The damping mechanisms of electrons and ions are included. The effects of coupling efficiency due to the edge plasma profile and the antenna configuration will be discussed.

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STUDY OF TURBULENT TRANSPORT DUE TO DRIFT-ALFVEN FLUCTUATIONS*

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Turbulent electron heat transport is a major loss mechanism in tokamaks. The effect of self-consistent magnetic fluttering has been recently analysed using clump theory[1]. An alternate approach has also been presented,[2] which includes perpendicular energy transport, and which leads to a revision of the previous conclusions. It uses the renormalized response function to determine the incremental fluxes due to perturbation of the mean density and temperature profiles.
The method is illustrated with a simple model with turbulent collision operator similar to the Balescu-Lenard operator. It is shown explicitly how drag and diffusion terms appear in this formalism.
In the context of drift Alfvén turbulence, the perturbations of thermodynamic fluxes across magnetic surfaces are evaluated for various sources, namely, in response to external sources of a) density, b) parallel temperature, c) perpendicular temperature, and d) parallel current, the fluxes of a) particles, b) electron parallel energy, c) electron perpendicular energy, and d) parallel current are computed. This transport matrix is analysed, and discussion of whether Onsager symmetry relations apply to the turbulent transport will be given. Other topics include non-resonant particle contribution to transport, anomalous resistivity, and electron heat transport.

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Effects of Radio-Frequency Fields on Transport

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Within the framework of quasilinear theory, it can be shown that rf may induce particle fluxes [1,2]. In the local WKB approximation, this is related to resonant absorption. In this approximation, we estimate the flux due to fast waves and ion Bernstein waves in the ion cyclotron range of frequencies. It is found that this flux is small for fast waves, but can be non-negligible for ion Bernstein waves. The magnitude depends on the ratio of poloidal to toroidal wave numbers and may reach a good fraction of typical experimental particle fluxes at reasonable wave and plasma parameters. More importantly, the direction of the flux depends locally on the sign of the local poloidal wave number so that there is a possibility of controlling particle flux through poloidal asymmetry of the rf. When the WKB approximation is relaxed, ponderomotive effects on non-resonant particles may also be included in quasilinear theory. The combined effects are considered within the framework of gyrokinetic formalism. The relative importance of these effects in different regions of a tokamak plasma will be discussed.

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A Universal Concurrent Algorithm for Plasma Particle-in-Cell Simulation Codes†

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We have developed a new algorithm for implementation of plasma particle-in-cell (PIC) simulation codes on concurrent processors. In particle simulations of plasmas, the orbits of thousands of individual plasma electrons and ions are followed as an initial value problem, where the particles move in the electric and magnetic fields calculated self-consistently from the charge and current densities created by these same particles. The new algorithm, the universal concurrent PIC (UC-PIC) algorithm, was designed to maintain processor load balance in situations with large spatial inhomogeneity in the plasma density. To decompose the problem using the UC-PIC algorithm, the physical domain of the simulation is divided into N_p sub-domains, where N_p is the number of processors, such that all sub-domains have roughly equal numbers of particles. If the plasma density is non-uniform, the sub-domains will be of unequal size. Each processor is assigned a sub-domain, with nearest neighbor sub-domains going to nearest neighbor processors. Since the sub-domains have nearly equal numbers of particles, the processors are properly load balanced. Dynamic load balancing is possible using the UC-PIC algorithm: if load imbalance occurs during a run as the plasma density evolves, sub domains can be re-created to balance the particle loads.

This algorithm has been utilized in a one-dimensional electrostatic PIC code implemented on the 32 node JPL Mark III Hypercube parallel computer. For a problem with an initially uniform density, the increase in speed in going from 1 to 32 processors for the dominant portion of code was 29, yielding an efficiency of 90%. Although implemented on a hypercube, this algorithm should be also be efficient on other parallel architectures and on sequential computers where part of the data resides in external memory, e.g., on a solid state disk.

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Stability Analysis of High Beta Poloidal Discharges in the Versator II Tokamak

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Recently the Versator II tokamak has achieved values of $\epsilon\beta_{\text{poloidal}}$ greater than one by operation at low toroidal field and low plasma current ($I_p = 5$ kA, $B_\phi = 7$ kG, $a/R_0 =$ 13cm/40cm). The plasma current in these experiments is generated purely by RF current drive and is carried by a low density, energetic (90 keV) tail. This energetic tail also dominates the pressure; the bulk electrons and ions both are cold (≈ 100 eV). Large outward shifts (5 cm) of the density and x-ray chord centroids are observed and are consistent with the predicted large outward shift of the magnetic axis expected at high beta and with the magnetic measurements. No gross instabilities have been observed experimentally although low level plasma fluctuations are currently being studied experimentally. These experiments are of interest in light of predictions by MHD theory that regions of second stability exist at high values of β_{poloidal} when the equilibrium distortions can be stabilizing. An analysis of the equilibrium and stability of these discharges is given using the Princeton MHD code for equilibrium and stability for various model pressure profiles. This code, however, assumes isotropic pressure which in this case is unrealistic since $P_{\|} >> P_{\perp}$ due to the RF tail. Preliminary results from an analytic treatment of stability near the magnetic axis which retains anisotropic pressure will be presented.

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Necessary Equilibrium Conditions for Advanced Toroidal Experiments

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The purpose of our study is to investigate, for various tokamak designs, the practical existence of ideal MHD equilibria, and to quantify the increasingly severe control problems which arise with greater poloidal field-shaping coil distance, with more strongly shaped plasma cross-section and with greater plasma elongation. This is done by examining the singular value decomposition of the transfer matrix between the coil currents and the loop fluxes. In earlier work, the viability of a tokamak was discussed in terms of the *first robustness parameter* [1], a related concept.

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Low β Stability of the DIII-D Tokamak

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The low β stability of the DIII–D tokamak has been investigated in detail. Results show that operation down to $q_s = 2$ (q_s is q at the limiter) is possible, but the stable window for $q_s > 3$ is severely limited by the *internal kink* to $q_0 \gtrsim 1.05$ and by internal modes to $q_0 \lesssim 1.25$ (q_0 is q on axis). The latter internal modes which have a different mode structure than kinks are destabilized by the high elongation and triangularity and the corresponding stability boundary is relatively insensitive to the shape of the current profile. The former, *internal kink* modes are stabilized by finite central shear and the stability boundary $q_0 \simeq 1.05$ is quite sensitive to the current profile shape. These modes are thought to be responsible for the giant sawteeth observed in JET [1]. With a suitably tailored profile, they can probably be avoided, in which case, kink stable operation down to $q_0 \sim 0.65$ would be possible. With more detailed tailoring, tearing modes could also be stabilized for $q_0 < 1$ [2], thereby allowing DIII–D to operate at q_0 values well below unity.

This is a report of work sponsored by the U.S. Department of Energy under Contract No. DE-AC03-84ER53158.

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NONLINEAR SATURATION OF BALLOONING MODES IN STELLARATORS

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3D codes are used to compare stellarators designed to have low parallel current with those having direct access to a second stability region [1]. Higher modes of the former seem to be less dangerous than those of the latter. Excellent resolution of the new spectral code BETAS is exploited to exhibit bifurcated equilibria on meshes of about 20,000 points. Nonlinear saturation of ballooning modes has been calculated in one field period for Heliotron E at high beta where the second stability region was expected to prevail. A torsatron winding law has been found that produces configurations with low parallel current and little variation of the magnetic field as beta increases. Its KAM surfaces are under investigation.

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PLASMA SHEATHS AND IMPURITY GENERATION BY ICRF ANTENNAS*

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In general, Faraday shield elements in an ICRF antenna are not aligned perfectly along the combined toroidal and poloidal magnetic fields and the inequality $\ell \gg g/\theta$ is fulfilled. Here ℓ denotes the length of a shield element, θ the misalignment angle, and g the gap between elements. The rf magnetic field $\tilde{B}_n$, which penetrates through the gap, induces a voltage $V \sim \omega \ell g \tilde{B}_n/\pi \sim 10^2$ volts across the gap. If the plasma density n in the gap satisfies $n \gg n_o \equiv 2\varepsilon_o V(eg^2) \approx 10^{16} m^{-3}$ then sheath phenomena close the gap and increase the electric field to $E \sim (Ven/\varepsilon_o)^{1/2}$. Hence ions acquire a quiver energy of $U = (eV/2)\omega_{pi}{}^2/\omega^2 \approx 10 - 100$ eV which is sufficient to sputter Faraday shield material. A one-dimensional Vlasov-Poisson equation is solved with a prescribed plasma source that maintains density to quantitatively investigate gap closure, electron multipactor, and sputtering.

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SHERWOOD THEORY MEETING 1988

Relation Between Beam Driven Seed-Current and Rotation in Steady State FRC*

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We consider an FRC configuration whose current is maintained by a steady state beam. Without quadrupole fields, back current can be inhibited by the Ohkawa effect if Z_{beam} is less than the Z_{eff} of the background plasma. However, the resulting rotation of the plasma often leads to instability. For systems with a large bootstrap effect, the rotation can be moderate, but it is then difficult to contain fusion products. An additional problem is the Ohkawa effect due to alpha particles which tend to disassemble the equilibrium. It has previously been shown that the presence of quadrupole fields can inhibit back current and a steady state flux can be maintained with moderate input power in both reactors and present day experiments. The resulting rotation seems slow enough to fulfill stability conditions. However, experimental means must be devised to supply a continual source of particles and additional energy.

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SHERWOOD THEORY MEETING 1988

Over Focusing in the Migma Configuration *

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One version of the Migma configuration is a disc of high energy ions, where axial length is much less than the radial scale length. The high energy ions are confined in a bounded phase space region so that they all pass close to the axis. In order to minimize synchrotron radiation, the configuration has been envisioned to have magnetic field excluded from its core. Blewett has designed such a magnet configuration with vacuum fields. It has also been suggested that diamagnetic currents can produce such a configuration in a more standard mirror-like geometry. Here we show that axial focusing can be too strong, and paradoxically cause axial expansion of disc configuration if the field excluded region is too extended. Similar considerations for the diamagnetic well place an upper limit on the beta of such a configuration to be of order $\beta \approx \frac{1}{2}/\ln\left(\frac{r_L}{b}\right)$, where r_L is the Larmor radius of an ion, and b the spread in distance of closest approach of the ions to the origin.

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SHERWOOD THEORY MEETING 1988

Stability of Energetic Ring Equilibrium of Large Orbit Ions *

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It has been proposed that a long field-reversed equilibrium of energetic large orbit ions in a charged neutralizing background of low temperature plasma could constitute the basis of a fusion reactor.[1] An important feature of this equilibrium is the very low ion density of the background plasma necessary to increase the slowing down time of the energetic ions. The stability of such equilibria to low frequency kink modes has been investigated by Lovelace.[2] The formal stability criteria is readily violated for long, annularly thin equilibria. However, the inertia of the background plasma ions play a significant role in the instability, and the kink mode is stable if the ratio of ion plasma density to ion beam density is below a critical threshold value. The stability analysis has been extended to explore (1) the effects of dissipation, and (2) the influence of a toroidal magnetic field and nearby conducting walls.

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SHERWOOD THEORY MEETING 1988

Orbit Stochasticity and Radial Diffusion*

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At low collisionality the distinction between magnetically trapped particles and circulating particles becomes an essential feature of toroidal plasma confinement. Thus neoclassical transport processes, as well as a variety of low frequency instabilities, are crucially affected by the existence of two types of orbits and, especially, by the boundary layer separating the trapped and untrapped regions of velocity space. In particular the collisional particle flux across this layer ultimately determines banana orbit decorrelation and therefore neoclassical diffusion. We point out that the same boundary layer is also especially sensitive to symmetry-breaking (or time-dependence) of the confinement geometry: asymmetric perturbations induce localized orbit stochasticity in the boundary layer, thereby affording an alternative, non-collisional path for separatrix crossing and banana decorrelation. Note that the phase space processes we consider are distinct from the configuration-space stochasticity of wandering magnetic field lines. By deriving a formulation of radial diffusion that pertains to both collisions and orbital stochasticity, we are able to estimate the level of symmetry breaking necessary to dominate Coulomb-collisional diffusion—a level much smaller than would be estimated for the case of a system without magnetic trapping.

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Rigorous upper bounds for passive turbulent advection*

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The theory of rigorous bounds on steady-state turbulent transport has a long history in fluid mechanics,[1,2] but has only recently been applied to plasma problems.[3] Historically, only self-consistent problems were considered,[2] but problems of passive advection are also of interest,[4] both physically and pedagogically. Our present understanding of the theory of bounds for passive advection will be described. The original "reference model" calculation of Krommes and Smith[4] will be reviewed, as will their extension to the simplest time-dependent constraint. (The latter is necessary in order to introduce the autocorrelation time into the formalism.) The theory of time-dependent constraints will then be generalized to allow various more complicated constraints. The utility and significance of these constraints will be considered. It is *not* true, for example, that more involved constraints—including, for example, certain effects of triplet correlation functions—necessarily lead to significant improvement in the bounds. However, one constraint involving fourth-order moments leads to a rigorous upper bound in excellent agreement with a numerical solution of the exact time-dependent (generalized reference model) stochastic partial differential equation; this nontrivial numerical solution is reported for the first time. Attention is given to the problem of particle transport in stochastic magnetic fields. This problem was considered briefly by Krommes and Smith. However, their calculation, though rigorous, failed to predict the most common quasilinear scaling[5] since the time-dependent constraint behaved as though the spatial autocorrelation length were ∞. It is shown how to generalize the time-dependent calculation to include *space*-dependent constraints in a practical way, and rigorous upper bounds are given that embrace the possibilities of both quasilinear and strong turbulence scalings. It is concluded that the bounding method is a viable approach for establishing both rigorous and useful predictions for transport in steady-state, highly nonlinear situations.

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Quasilinear evolution of the mean poloidal magnetic flux in a tokamak due to tearing mode turbulence*

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It has been argued[1,2] that the "hyper-resistivity" $D_{\rm h}$ (defined as the coefficient of the second-order derivative of the mean current in the evolution equation for the mean poloidal magnetic flux) due to a bath of tearing mode turbulence plays an important role in the evolution and relaxation of the current profiles in tokamaks and reversed-field pinches. Ultimately, one is interested in the $D_{\rm h}$ due to steady-state turbulence. However, the result remains somewhat unclear even in the regime of strictly quasilinear evolution. Various authors[1,2] have obtained apparently different results for the quasilinear $D_{\rm h}$ and the associated turbulent resistivity $\eta_{\rm t}$, and the physical pictures behind those results were not always stated clearly. In the present work the calculations of the quasilinear $D_{\rm h}$ and $\eta_{\rm t}$ are reconsidered from a form of initial value approach, generalized to embrace the difficulties associated with radial inhomogeneity and the presence of multiple resistive layers. Various relative orderings of the rational surface spacing, island size, and resistive layer width are considered, and the orderings associated with the results of Bhattacharjee and Hameiri[1] and of Strauss[2] are determined; these orderings are not necessarily consistent with the assumption of stochasticity or with exponential growth of the modes. Because in the simplest picture the modes have no real frequency, the inverse of the linear growth rate γ plays the role of an autocorrelation time, unlike more familiar situations where $\gamma \ll \omega$. The role of symmetry properties in determining the values of $\eta_{\rm t}$ and $D_{\rm h}$ is described, and subtleties associated with various coarse-graining procedures are explored. Although qualitative remarks about the nature of the turbulent steady state are also presented, it must be stressed that deep issues related to the very nature of tearing modes in the presence of stochasticity remain to be resolved.

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Averaging of Nonlinear Wavetrains

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A common problem in plasma physics is that of a narrow-banded (nearly monochromatic) wavetrain propagating in a weakly nonlinear medium. In such a situation, it is desirable to eliminate the rapid carrier oscillations in favor of a reduced equation which describes the dynamics of the wave envelope. This is commonly done by making the following ansatz:

$$A(x,t) = u(X,T)e^{i(kx - \omega t)} + c.\ c.,$$

where A(x,t) is the 'full' wave, and u(X,T) is the wave envelope, which is assumed to depend only on the large-spatial-scale and long-time-scale variables X and T. This procedure invariably leads to a nonlinear Schrödinger-type equation (NLS), whose simplest form is given by:

$$iu_T + u_{XX} \pm 2|u|^2u = 0.$$

This equation is exactly solvable by inverse scattering techniques (IST), a method of solution which relates the wave u(X,T) to a set of abstract scattering data. An open question concerning this approach has been the correct physical interpretation of the scattering data. By examining the NLS limit of another equation exactly solvable via IST, namely the Korteweg-de Vries (KdV) equation ($u_t + uu_x + u_{xxx} = 0$), we arrive at the simple result that the NLS scattering data is the 'average' of the KdV scattering data. Relationships between the conservation laws for the NLS and KdV will also be discussed.

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Numerical Simulation of Tearing Modes in a Tokamak

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The parallel component of Ohm's law can be extended to incorporate the effect of MHD fluctuations by the introduction of a space-time dependent diffusion coefficient for the parallel current.[1] The new term in the Ohm's law enhances the dissipation of mean field energy, but does not enhance the dissipation of field helicity. We plan to use the new term to simulate tearing modes in a tokamak.

We solve the parallel Ohm's law in a cylinder for the poloidal flux evolution. The equation has the form of a simple diffusion of the flux along with the new current smoothing term. We extend the Crank-Nicolson method for solving the diffusion equation numerically to include the effect of the smoothing term.

We plan to simulate tearing modes by performing a marginal stability analysis.[2] The analysis can be used to predict the width of magnetic islands using the Rutherford formula for island growth. The diffusion coefficient for the parallel current can be made large near the islands, effectively smoothing the current profile in that region.

As a further study, we plan to use our computer code to examine problems relating to current drive utilizing the bootstrap effect.

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Stochastic Electron Cyclotron Heating for Current Drive *

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We consider the possibility of driving electron current in a tokamak by using short bursts of very intense electron cyclotron waves propagating at an angle to the toroidal magnetic field. These waves are assumed to be generated by a pulsed free electron laser which is focused to a small spot size within the plasma. Electric fields in the range of $E/Bc \sim 0.1$ can cause the relativistic cyclotron harmonic resonances to overlap, resulting in stochastic acceleration of electrons to the MeV range of energies. This process has been studied recently for ionospheric heating. [1] A finite wavenumber in the toroidal direction causes acceleration in the direction of the wave momentum, resulting in a toroidal electron current. Because electrons can reach high energies in one pulse, the current-drive efficiency of this process can be relatively high, with $nIR/p \sim 0.4$ $[10^{20} A/m^2 W]$ for $E/Bc \sim 0.2$. We calculate the efficiency by combining the numerical integration of the orbits of an ensemble of electrons passing through an rf pulse together with a calculation of the collisional decay of the heated electrons. Using a wave with the x-mode polarization at a frequency just below the second harmonic appears optimal.

We also investigate effects which tend to reduce the efficiency such as electron trapping in the magnetic well and synchrotron radiation. Taken together, these effects can reduce the efficiency by a factor of ~ 2, but the reduction is parameter dependent. Parametric instabilities may be excited by the intense rf as well.

Current drive calculations will be presented for the Microwave Tokamak Experiment (MTX) at Livermore and for larger reactor-scale tokamaks such as ITER.

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Sherwood Theory Conference
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Alfven Wave Propagation and Absorption
with Linetied Boundary Conditions*

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We investigate numerically, using reduced MHD, Alfven wave propagation and absorption in periodic and finite length current carrying cylindrical plasmas. In the periodic case such as a tokamak, resonant absorption is expected to occur. On the other hand, in a linetied magnetic field, such as in the solar corona or earth's magnetosphere, Alfven waves may take a ballooning structure which prevents absorption. Numerical results will be presented.

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**currently at Cornell University

HYPER-RESISTIVITY OF VERY DENSLY PACKED TEARING MODE TURBULENCE

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The analytic theory of long wavelength collisional tearing turbulence[1] is reexamined, paying particular attention to the strongly overlapping island limit (densly packed) of the back reaction of the JxB force on Ohm's Law. This back reaction takes the form of an anomalous hyper-resistivity and negative resistivity, which could play a role in current relaxation in RFPs and fast reconnection in astrophysics[2]. Specifically, the effects of collisional resistivity are self consistently included in the solution of the driven equations. The inclusion of resistivity is shown to strongly affect the anomalous hyper-resistivity and negative resistivity in the very densly packed limit of the renormalized Ohm's Law. The hyper-resistivity is nonzero in this limit and exhibits different scalings with resistivity, shear, and mode width than previous results[2].

The dynamics of mean square flux and energy are discussed in light of the above back reaction effects. Mean square flux is found to be analogous to helicity and thus the hyper-resistivity can be related to the result of Boozer[3]. The role of back reaction effects in energy equipartitioning is identified. Saturation mechanisms for stationary turbulence are examined, along with the role of back reaction in explosive growth.

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2D15

THE ROLE OF $M = 0$ MODAL COMPONENTS IN THE RFP DYNAMO UNDER THE MHD MODEL

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The role of the $m = 0$ modal components on the RFP dynamo is examined under the MHD model by comparing results with and without various nonlinear convolutions of the $m = 0$ spectrum. Results indicate that the dynamo comes directly from the $m = 1$ drivers and the effect on the dynamo of other nonlinear convolutions is small.

MHD STUDIES OF THE TILT MODE IN A FIELD-REVERSED CONFIGURATION

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Both MHD and Kinetic theory predicts that the internal tilt mode (ITM) in FRC's should be unstable; however, it has never been observed experimentally. We have been using a 3D semi-implicit, resistive MHD code [1] to study the effect of various terms that are normally neglected.

Inclusion of the Hall term leads to a reduced growth rate for small s (s is a measure of the number of ion gyroradii separating the field null from the separatrix), and a scaling of growth rate with s similar to that predicted by kinetic theory. This is also in agreement with an analytic model [2].

Experimentally, FRC's are observed to rotate. Inclusion of this effect at the observed rotation rates has almost no effect, but at larger rates (Vo at the separatrix near sonic), the character of the tilt changes. Rather than an internal mode, we observe gross distortion of the separatrix as the axial shift has no radial component associated with it. The growth rate is similar to that of a non-rotating case. A rapidly rotating short FRC with strong mirrors (problemak like geometry), however, is found to be stable. This work will be extended to determine if this still holds for greater elongations.

MHD formation codes predict equilibria with flux maxima near each end, in contrast to equilibrium codes which always assume the maximum flux is at the axis of symmetry. The effect of these different equilibria on the growth of the ITM will be examined. Additionally, the effect of randomly exciting several modes, rather than initializing the problem with a coherent n=1 perturbation, will be examined.

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SHERWOOD THEORY MEETING 1988

Simulation of Driven 2-D Microtearing Mode Turbulence*

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Initial studies of driven, fully developed microtearing mode turbulence in 2-D have been undertaken using a simple model and a truncated spectral code. The model consists of magnetic flux and density evolution equations coupled by parallel pressure in Ohm's law and parallel compressibility in the density equation. Turbulence is driven by the time-dependent thermal force at small k_x and large k_y and damped at large k_x and k_y by the resistivity. Diamagnetic rotation is included in Ohm's law and a viscous-like dissipation in the density equation is also considered. Isotropic spectra for mean square flux which are peaked at low k_x and k_y are obtained when dissipation is absent, suggesting an inverse flux cascade. With dissipation (driving and damping), two classes of saturated states are observed: saturation with magnetic and internal energies roughly equal and saturation in which equipartitioned energies do not occur. The total energy in both types of steady states is the same. When magnetic energy E_m initially exceeds internal energy E_k, a rapid approach to rough equipartition with $E_m \gtrsim E_k$ is observed. This relaxation is governed by the anomalous hyper-resistivity which occurs in one-point renormalizations of the model equations. Spectra of mean square flux and eddy decay times are obtained and compared with a simple saturation criterion based on the balance of the time-dependent thermal force with the anomalous hyper-resistivity. When $E_k > E_m$ initially, the steady state is not equipartitioned and internal energy remains larger than magnetic energy, if viscosity is absent. This steady state involves balances with incoherent terms neglected in one-point theory and hence cannot be described by one-point theory or solely in terms of the hyper-resistivity. The addition of finite viscosity causes the state with $E_k > E_m$ to decay to an equipartitioned steady state with a decay rate proportional to both the viscosity and the diamagnetic rotation. This decay is much slower than typical eddy turnover times for large Reynolds number turbulence, and must also involve balances with incoherent terms.

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LINEAR AND NONLINEAR SIMULATIONS OF RESISTIVE MHD INSTABILITIES IN A POLOIDAL DIVERTOR TOKAMAK*

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The 3-D resistive MHD initial value code RPD[1,2] is being used to study the linear and nonlinear evolution of long wavelength resistive MHD instabilities in a four-node poloidal divertor tokamak. Distinguishing features of this work are inclusion of the region outside the divertor separatrix and inclusion of full toroidal effect in the simulation runs.

The m=2,n=1 tearing mode tends to be linearly stabilized when the q=2 surface is brought close to the divertor separatrix. On the other hand, the m=1,n=1 resistive kink mode remains linearly unstable for $q_{axis} < 1$ regardless of the proximity of the q=1 surface to the divertor separatrix. When a plasma current is added to the region outside the divertor separatrix, the 2/1 mode is found to be strongly stabilized as the result of a profile modification. A similar stabilization effect is seen for the 1/1 mode, but to a lesser extent. However, a mere addition of the plasma current to the region outside the divertor separatrix without much altering the current profile inside the divertor separatrix does not have an appreciable stabilization effect on the 2/1 and 1/1 modes.

Nonlinear runs of the 2/1 tearing mode demonstrate the saturation of the 2/1 magnetic island. If the q=2 surface is sufficiently close to the divertor separatrix, significant stochasticity of the magnetic field develops before the saturation of island growth. As for the 1/1 resistive kink mode, both partial and total reconnections of the 1/1 magnetic island are found. There is an indication that the 1/1 island may saturate nonlinearly depending on the resiliency of the divertor separatrix. The exact physical mechanism that determines the type of 1/1 nonlinear evolution is under investigation.

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2D19

AXISYMMETRIC STABILITY STUDIES OF TOKAMAK PLASMAS*

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We have performed a series of TSC calculations to understand the axisymmetric stability and control properties of both CIT (1.75 m design) and Asdex-U (single null and double null). The high elongation of CIT, in particular $\kappa \sim 2$ at the 95% flux surface, makes control of this instability a critical element in the machine design.

We have calculated the passively stabilized resistive growth rates of CIT equilibrium at different times during the start-up phase to show that the instability remains amenable to control during the entire discharge. We have also investigated the sensitivity of the instability to the separation distance of the stabilizing conducting walls. Convergence studies in the artificial mass enhancement parameter FFAC have been performed to obtain the converged zero-mass growth rate.

Active control has been studied by using a two tier feedback control system based on flux loop sensors, and on control coils located both inside and outside the toroidal field magnets. We are determining the stable range of proportional and derivative feedback coefficients for given time delays due to control processing.

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FOKKER-PLANCK CODE FOR CURRENT DRIVE IN TOKAMAK*

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We have developed a bounce-averaged, multiregion Fokker-Planck code, SMOKE, to study current drive in tokamaks. The code uses a finite element method which enables us to take care of the rapid variation of rf coefficients in phase space without employing such a fine grid as used in finite difference method. SMOKE is capable of studying ECRH, lower hybrid, and neutral beam current drive schemes. It can also treat potential along a field line and a double magnetic well of a beam-shaped tokamak such as PBX. We first compare ECRH current drive efficiencies from the code with the analytical results of Cohen[1] which include trapped particle effect. We then investigate the degradation of efficiency due to harmonic overlap. These results will be reported.

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SPHERICAL HARMONIC EXPANSION FOR THE RELATIVISTIC COLLISION OPERATOR*

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Recently[1] we presented a differential formulation of the relativistic collision operator of Beliaev and Budker.[2] Here we solve the resulting differential equations for the potentials by separation of variables in spherical coordinates. The angular dependence is given by spherical harmonics, and the radial equation may be solved in terms of associated Legendre functions of half-integer order and degree. We can thereby express the potentials in terms of one-dimensional integrals over the distribution function. In the non-relativistic limit, these integrals reduce to those given by Rosenbluth, MacDonald, and Judd.[3]

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THE COILLESS TOKAMAK

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The coilless tokamak is a configuration that achieves a tokamak like magnetic field and q-profile without using any external toroidal field or ohmic heating coils. The resulting elimination of material linking the hole in the torus could lead to a much simpler and less expensive reactor design.

This poster will describe the use of a code that computes axisymmetric ideal MHD equilibria in a general compact boundary to find a specific boundary shape that will produce a tokamak like q profile for a plasma in a near minimum energy state. Equilibria have been found with $q \approx 1$ on axis and $q \approx 3$ at the wall, and with Mercier beta limits of over 6% volume averaged (engineering betas up to 10%). Since these equilibria are near minimum energy states, they can be formed and sustained in steady state by simply injecting magnetic helicity into an appropriately shaped flux conserver. Plasma relaxation will automatically create and maintain the proper field structure.

2D23

IONIZATION EFFECTS ON TOKAMAK EDGE TURBULENCE

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ABSTRACT

It is widely recognized now that edge turbulence may indirectly be playing a crucial role in determining the overall bulk particle and energy confinement in tokamak plasmas. There is also substantial agreement on the point that collisional plasma instabilities like the density gradient driven drift-dissipative instability and the resistivity-gradient driven rippling instability are the dominant sources of tokamak edge turbulence. In this paper it is demonstrated that inclusion of ionization effects leads to a substantial enhancement in the growth rate of above mentioned plasma instabilities. A local analysis of the drift-dissipative instability is carried out first. Next, the calculations are extended to the more realistic case of a plasma with magnetic shear and toroidal effects; however, the complications due to electron temperature fluctuations are ignored in this case. Finally, the theory of rippling modes in a plasma with ionization effects included, is presented. Using simple scaling arguments, estimates are also provided for the modified particle/energy diffusion coefficients in the presence of ionization effects. The predicted enhanced edge transport is likely to be in much better agreement with experimental measurements on tokamaks like TEXT, TOSCA etc. It is also likely that the improved confinement observed during the H-mode and the supershots are related to the decreased ionization and recycling effects at the plasma edge.

Neutral Particle and Parallel Plasma Transport in Pump Limiters

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Neutral particle transport and the transport of plasma along field lines in the high neutral density environment of scoop and pump limiters are investigated. The plasma density, flow velocity, ion temperature and electron temperature in the limiter throat are computed from 1-D fluid equations. Longitudinal ion viscosity and heat conduction terms are included in the momentum and energy balance equations, but cross-field diffusion is neglected. The neutral transport in the limiter, as well as particle, momentum, and energy source terms due to plasma-neutral interactions are described by the code DEGAS. The fluid equations are integrated from the limiter throat to the neutralizer plate, with temperature and flow velocity gradients at the throat treated as parameters. The effect of selective recycling of re-ionized neutrals in the limiter throat is investigated. Results are compared to Langmuir probe and pressure measurements from the ISX-B pumped limiter experiment. Preliminary calculations for the Tore Supra outboard pumped limiter module are reported.

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SHERWOOD THEORY MEETING 1988

Effect of an Iron Core on Plasma Positional Stability*

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The presence of an iron core introduces a major perturbation to the magnetic configuration of a tokamak. The standard definition of field index, $n = -\frac{R}{B_{v0}}\frac{\partial B_v}{\partial R}$, ignores the fact that part of the vertical field is produced by the coupling of the iron core and the plasma itself. A new definition of the field index should include $\frac{dB_v}{dR}$ (for in-out stability) or $\frac{dB_r}{dz}$ (for up-down stability), accounting for the different fields produced when the plasma is displaced. In TEXT the difference is significant. With the new definitions, we explore a transfer function approach to the position feedback system design. The effect of eddy-currents induced in the vacuum vessel is included in the model.

The application of this study is to identify the equilibrium and stability requirements for TEXT Upgrade. The modified tokamak will incorporate divertor coils producing x-points on the inside of the plasma major radius. This will allow the study of L to H-mode transitions.

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CANDIDATE MODE FOR ELECTRON THERMAL ENERGY TRANSPORT*

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The subject of anomalous electron energy transport is of considerable importance for fusion research. In order to qualify as a good candidate for this transport, a microinstability should have the following properties:[1] (1) it should be driven by an electron temperature gradient, (2) it should be active over a significant portion of the plasma column, transporting heat to its edge, (3) its wavelength should be long enough to cause energy transport over macroscopic scales, (4) it should produce particle transport that is smaller than the energy transport. We have analyzed the linear and quasilinear theory of the ubiquitous mode[2] which is driven unstable by the combined effects of an electron temperature gradient and trapped electrons. The integro-differential dispersion equation has been solved in toroidal geometry, including the effect of collisional detrapping of electrons. The instability have been found to persist with little change in growth rate over three orders of magnitude in $b_i = k_\perp^2 v_{Ti}^2/2\Omega_i^2$ and four orders in $\nu_e^* = \nu_e/\varepsilon\omega_{be}$ (ω_{be} = bounce frequency) and with strongly increasing growth rate as $\eta_e = d\ln T_e/d\ln n$ increases [cf. (1) - (3)]. Quasilinear theory indicates that the heat flux is (in dimensionless units) typically an order of magnitude larger than the corresponding particle flux [cf.(4)].

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ENERGY CONFINEMENT IN TURBULENT FLUID PLASMAS

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Scaling laws for energy confinement in a turbulent plasma dominated by pressure-driven modes are revisited. The method of local invariance introduced by Connor and Taylor[1] is used to compute new scaling laws[2] for electromagnetic turbulence under a consistent low-β approximation for reversed-field pinches (RFP's) and tokamaks. For collisionless transport along stochastic magnetic fields, the electron thermal diffusivity is larger by a factor of β^{-1} for the RFP, and $\varepsilon/\beta q^2$ for the tokamak, compared with the predictions of earlier theories[1,3] on electrostatic turbulence. (Here β is the plasma beta, ε, the aspect ratio and q, the safety factor.) The energy confinement time for RFP's scales as $\tau \sim (a^2/6\eta)(m/M)^{1/2}\beta^{-1}$, and for tokamaks as $\tau \sim (a^2/6\eta)(m/M)^{1/2}\varepsilon^{1/2}\beta q$, where a is the plasma radius, η, the resistivity, and M/m, the ion to electron mass ratio. For Ohmically heated RFP's, we obtain $\beta \approx (m/M)^{1/4}$ irrespective of machine parameters, which is somewhat lower than earlier predictions.

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Application of an Improved Relativistic Absorption Model for Electron Cyclotron Current Drive

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The efficiency of electron cyclotron current drive in a tokamak is a complicated function of many parameters. Its evaluation requires a ray tracing code with an appropriate absorption model and current computation or a bounce-averaged Fokker-Planck code. TORAY [1] is the most advanced code of this type for the linear regime. However, the working model [2] of relativistic absorption in TORAY is based on the use of Poynting's theorem with a wave vector and polarization computed from the cold plasma dispersion relation. Thus the model is not applicable for absorption around the fundamental cyclotron frequency. This has limited TORAY to a nonrelativistic absorption model with a relativistic current computation at the fundamental.

The model has been improved by computing a wave vector and polarization from the warm plasma dispersion relation. The verification of the model against a complete self-consistent computation of the relativistic dispersion relation [3] will be reported. With this improved model, it is possible to obtain a factor of 2 or 3 larger current drive efficiency for the fundamental electron cyclotron waves. The dependence on launch angle differs substantially from the previous result for the inside launch extraordinary mode.

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Alpha Particle Induced Oscillation Bursts in Burning Tokamak Plasma and the Effects on Ash Control

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The fishbone oscillations due to the trapped alpha particles in burning plasma of CIT and ITER are considered using a simple analytical model. The expected oscillation frequencies are computed using a few varying set of parameters including the density, current profile and alpha particle losses. We also consider the case of a fairly low shear region near the center of the plasma and develop analytical formula for the fishbone oscillations for the low-shear q profile using large aspect ratio low-shear theory for the internal kinks. Finally, the trapped particle destabilization of the internal kink mode due to the presence of the alphas and the hot particles is considered as a viable candidate for the removal of the slowed-down alphas. The possibility of ash control and/or the removal of the low to medium energy alphas using fishbones is also discussed. The necessary current profile shapes that can efficiently remove low-energy alphas by exciting the trapped-particle branch of the ideal internal kink are indicated.

Electron Cyclotron Emission from ECH and Ohmically Heated Tokamak Discharges

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Estimates of cyclotron emission spectra for ohmic and electron cyclotron heated tokamak discharges are obtained with a new computer code HORACE which incorporates ray tracing and a relativistic determination of the absorption and emission coefficients. The distribution functions used by HORACE are obtained from the CQL3D Fokker-Planck code [1], that is, 2D-in-momentum-space, bounce-averaged electron distribution functions on a radial array of flux surfaces consistent with ECH power deposition/quasilinear diffusion, and ohmic heating. The ray tracing and wave polarizations are based on the cold plasma dispersion relations. Emission and absorption coefficients are calculated from the distribution functions by numerically integrating the relativistic expressions given by Bornatici and Ruffina [2]. Given these coefficients along the rays, the wave energy transfer equation [3] is solved to obtain the net emission into the detector. The code has been benchmarked by (1) comparison with second harmonic absorption obtained by the Culham and TORAY ray tracing codes, (2) comparison with nonthermal emission and absorption coefficients in Ref. 2, and (3) satisfaction of Kirchoff's Law for Maxwellian distributions [4]. The code is used to predict cyclotron emission which will be observed by a new broad-band ECE detector on the DIII–D tokamak [5], and to interpret ECE observations of ECH induced electron runaway discharges in the Leningrad FT-1 tokamak [6].

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Sherwood Theory Conference

A Kinetic Model for Tearing Mode Layers in a Torus

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In order to discuss the stability of tearing modes in high temperature toroidal plasmas a realistic model for the dynamics in the tearing layer is required. For low values of the poloidal mode number m the neo-classical fluid model, considered by Callen and Shaing[1] for example, is relevant, while at high values of m the kinetic trapped particle calculation of Catto and Rosenbluth[2], valid for $\omega_* > \nu_{eff}$, is appropriate. However, there is an intermediate range of m, important for the micro-tearing modes that might be responsible for anomalous transport, for which neither treatment is valid. This regime, defined by $\nu \lesssim \omega_* < \nu_{eff}$, was considered previously[3], using a Krook collision term for the trapped particles. This led to growth rates $\gamma/\omega_* \sim \varepsilon^{1/2}\, \omega_*/\nu_{eff}$. However the problem involves a boundary layer around the trapped region of velocity space so we have examined the effects of a more realistic Lorentz collision operator. We find the effect of trapped electrons on the growth rate $\sim \varepsilon^{1/2}\left(\frac{\nu}{\omega_*}\right)^{1/2}$ but collisional effects on the bulk of passing particles can be more important.

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Thermal Alpha Effect and Control for ETR-type Reactor

by

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Abstract

The effect of thermal alpha ash accumulation on the plasma performance of an ETR-type reactor, like TIBER II, has been investigated using a 0-D model. With a combination of neo-Alcator ohmic scaling and Kaye-Goldston auxiliary heated scaling, the results show that at $T \approx 16$ KeV the ignition window (constrained by the Murakami density limit and 0.75 Troyon beta limit) closes with ~ 5% ash concentration and the driven window (i.e. the auxiliary power $\neq$ 0) closes with ~ 14% ash concentration. With good confinement, e.g. H mode, near neoclassical transport can result in ash concentrations well above these values. Clearly then, an active ash control is required for an ETR-type reactor. We have completed a preliminary investigation of several possible control methods, such as beam driven flow reversal, electric field pumping, controlled wave pumping, and controlled instability pumping. Among these methods, controlled sawtooth instability pumping seems to be one of the most attractive based on a consideration of the input power requirement and relative selectivity. Examples of application of this technique to an ETR scale reactor based on 1-1/2 D calculations will be presented.

CONDITIONS FOR FUSION WITH MINIMAL NEUTRON PRODUCTION*

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Compact, high field toroidal machines appear to offer the possibility[1,2] of reaching conditions for steady state burning of fuels that produce relatively few neutrons, i.e., D-^{3}He mixtures. The conditions for steady state burning of these fuels depend sensitively upon the relative concentrations of the trace reaction products, p, T, and ^{4}He, in a way that D-T burning does not. Synchrotron radiation plays an important role. The D-D reaction, defined as having no external fuelling of ^{3}He, is even more sensitive than D-^{3}He. The energy balance becomes more favorable with increasing (D) density, but the plasma β also approaches the MHD stability limit. The MHD stability and the steady state conditions also depend sensitively on the spatial distributions of the plasma parameters. These problems are considered in detail numerically.

Ignition of D-^{3}He mixtures starting from D-T burning introduces the problems of ash accumulation (^{4}He) and particle fuelling. Ash accumulation can prevent direct ignition of D-D and is a serious consideration for D-^{3}He. The possibility of central, hot fuelling, perhaps through an inward particle pinch, is an important factor. The time evolution for possible ignition is investigated with a 1D transport model. Similar results can be applied to the fusion burning phase of D-T experiments.

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Relating Resistive and Adiabatic Alternating Dimension Codes

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The problem posed here is to relate the solutions of slow evolution resistive MHD equations[1] at the low resistivity end to solutions of adiabatic MHD equations[2]. Both systems are solved by alternating dimension methods but the given data for the two kinds of problem are very different. For the test problem treated here, a 2-D doublet configuration, the low resistivity solutions are computationally difficult to obtain and slow to run. Our ultimate goal is to approximate low resistivity solutions by using the much faster running adiabatic code. Here we show how to find an appropriate adiabatic solution which approximates a given low resistivity solution. We compare computational results for the two systems.

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Statistical Dynamics of a Two Field Model of Drift Wave Turbulence

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The statistical dynamics of a two-field model of low frequency plasma turbulence is discussed. Equilibrium statistical mechanics based on a generalized H-theorem is used to calculate the equilibrium kinetic energy $\langle(\nabla\hat{\phi})^2\rangle$, fluid enstrophy, potential energy $\langle\hat{n}^2\rangle$ and aligment $\langle\hat{n}\hat{\phi}\rangle$ spectra. Results indicate that breaking the adiabatic relation $\hat{n}/no = e\hat{\phi}/T_e$ (i.e. in the two field model) allows transfer of total energy to small scales which is in distinct contrast to the well-known one-field result. Furthermore, the fact that $\langle\hat{\phi}^2\rangle$ and $\langle\hat{n}^2\rangle$ accumulate at different ends of the wave number spectrum naturally constrains the magnitude of the alignment spectrum. Carnevale type H-functions [1] for the one and two field models have been constructed in terms of the second order moment spectra. Maximization of this H function recovers the equilibrium spectra obtained by using the Gibbs ensemble theory. A Boltzmann type H-theorem has been proved for the one field and two field (with $\langle\hat{n}\hat{\phi}\rangle = 0$) closure models. We thus speculate that it should now be possible to determine enstrophy production rates associated with turbulent relaxation and that the inequality of these rates underlies the notion of "selective decay". These predictions will be tested by numerical solution of the isotropized, stirring-and-dissipation-free closure models. Finally, a complete system of closure equations for the two field model has been derived and will be discussed.

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Drift Wave Model Tokamak Ignition Projections With a Zero-Dimensional Transport Code

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A zero-dimensional transport code is formulated using theoretical drift wave models with an *ad hoc* q-dependence. The theoretical models are normalized to tokamak confinement time data over a wide range of density, field, and size (ISX, TFTR, DIII, DIII–D, JET) for L and H modes. The fit coefficient for the dissipative trapped electron (DTE) mode is fixed by low density ohmic discharges and that for the ion temperature gradient (ITG) mode by beam-heated discharges. While the theoretical models are almost indistinguishable from the standard (Kaye-Goldston) empirical model in fitting the available data, it is shown in detail that they have significant quantitative and qualitative differences on projection to ignition in the proposed Compact Ignition Tokamak. The empirical model fails to account for the DTE unfavorable temperature scaling masked by the ohmic heating identity and the ITG favorable density scaling masked by beam penetration and impurity line radiation effects in present experiments. The ignition conditions are analyzed with explicit formulas for the minimum required auxiliary power P_{m} and a figure of merit F_{M} given essentially by the radio of β_{MHD} to the minimum β on the ignition curve $B_{\mathrm{M}}[F_{\mathrm{M}} = B_{\mathrm{M}}^{5/6}$, $Q_{\mathrm{M}} = 5\,F_{\mathrm{M}}/(1 - F_{\mathrm{M}})]$. Both P_{m} and B_{M} have strong favorable scaling with size (a) and field (B) and dependent sensitivity on the normalization of confinement time within the scatter of the data $\hat{f} = \tau_{\mathrm{exp}}/\tau_{\mathrm{model}}$: for the DTE mode $P_{\mathrm{m}}^{-1} \propto \hat{f}_{\mathrm{OH}}^{2.5} a B^2$, $B_{\mathrm{M}} \propto \hat{f}_{\mathrm{OH}}^{1.2} a^2 B^3$; and for the ITG mode $P_{\mathrm{m}}^{-1} \propto (\hat{h}\hat{f}_{\mathrm{aux}})^5 a^3 B^4$, $B_{\mathrm{M}} \propto (\hat{h} f_{\mathrm{aux}})^{2.5} a^3 B^4$ where $\hat{h}$ corresponds to the factor 2.5 improvement in H over L confinement time. Clearly when ITG dominates $P_{\mathrm{m}}^{\mathrm{H}} \sim O\,(0.01)\,P_{\mathrm{m}}^{\mathrm{L}}$ and $B_{\mathrm{M}}^{\mathrm{H}} \sim O\;(10)\,B_{\mathrm{M}}^{\mathrm{L}}$. The minimum ignition densities n_{m} are well above ohmic density limits scaling with current density, but it is demonstrated that sufficient auxiliary power can burn out line radiation allowing operation at higher densities.

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Power Requirements of Current Drive

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Entropy arguments imply that the minimum power required to maintain a distribution function $f(\mathbf{p})$ is $P_c = -T \int \ln(f/f_M)\, C(f)\, d^3p$ with f_M any convenient Maxwellian distribution, $\mathbf{p}$ the momentum, and $C(f)$ the collision operator. The only important limitation on the use of the formula for P_c is that the non-Maxwellian part of $f(\mathbf{p})$ should contribute negligibly to the energy, so the temperature T is well-defined. The minimum power that is required to maintain a current using different types of carriers can be calculated using P_c. One can show that the minimum power required for a current drive scheme that utilizes tail electrons is $E_r j$ with $E_r \approx 0.09\, n_{14}$ volts/meter, n_{14} the electron density in units of 10^{14}, and j the current density. This is the same power that is required to maintain a runaway discharge. One can also determine the power that is required to maintain a current using a tail on the ion distribution function. Current drive power scales with the mass and the velocity of tail carriers as $1/mv^2$. For electrons, the $1/mv^2$ scaling is limited by v=c, and for ions, the scaling fails when the ions exceed the critical energy, $(m_i/m_e)^{1/3}T_e$, so their drag is dominated by the electrons. Since the critical energy in a reactor is comparable to m_ec^2, current drive schemes that use either electron or ion tails require comparable power. One can also show that if one can drive a current with waves that interact with particles of a significantly higher energy than the phase velocity of the waves then it is possible to recover the Ohmic formula ηj^2 for current drive power. This work is supported by the grant DE-FG05-84Er53176 from the U.S. Department of Energy.

ANALYTIC APPROACH TO ERROR FIELD PERTURBATION PROFILES IN AN RFP*

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In previous work, we have numerically simulated the response of an RFP plasma to external error field perturbations. A salient feature of the results was the alteration of the radial profile of the error field inside the plasma volume by the RFP plasma. In particular, the b_r associated with the error perturbation was reduced from its value for a vacuum profile at the resonant surface ($\underline{k} \cdot \underline{B}_o = 0$), for modes with poloidal mode number m=0. It was observed that this behavior depends on the equilibrium fields (specifically on $\lambda' \equiv d/dr(\underline{J}_o \cdot \underline{B}_o/B_o^2)$) and on the coupling of the magnetic field to the flows by resistivity (η) and viscosity (ν_o). The goal of the present work is to understand this interesting reduction in b_r and to quantify its dependence on λ', η, and ν_o.

The method chosen was the solution of the steady-state, linearized MHD equations. The dissipative (η, ν_o) effects were assumed to be confined to a small layer around the resonant surface (r_s) in the $\lambda' \neq 0$ region. The higher order equations were solved in this layer and matched to solutions of $\underline{J} \times \underline{B} = 0$ in the "outer" regions with $\lambda' \neq 0$. Results to be presented include:

- Layer width, L, and its dependence on ν_o and η.
- $b_r(r_s)$ and its dependence on λ', ν_o, and η.
- Profiles of v_r and b_r showing the effects of the dissipative layer.

Also, comparisons will be made with numerically obtained scalings of br, v_r, and L with η and ν_o.

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RF CURRENT DRIVE "EFFICIENCIES" DERIVED USING KLIMA'S RELATION

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ABSTRACT

Current drive "efficiencies" for high phase velocity ($\omega/k_z \gg u_{Te}$, e.g. lower hybrid) and low phase velocity ($\omega/k_z < u_{Te}$, e.g. Rotamak) schemes are derived from Klima's general relation between momentum and energy fluxes. Comparison with the Fisch-Boozer lower hybrid efficiency reveals that Fisch-Boozer overestimate lower hybrid current drive efficiency by a factor of two. By taking into account the effect of fast particle losses on lower hybrid drive, Luckhardt's recent results are easily deduced (corrected by the same factor of two). Finally, the $\omega/k_z \gg u_{Te}$ and $\omega/k_z \ll u_{Te}$ efficiencies presented here are shown to be in good agreement with lower hybrid current drive experiments and Rotamak current drive experiments respectively.

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THE EVOLUTION OF RESISTIVE BALLOONING MODES IN THE BANANA-PLATEAU COLLISIONALITY REGIME*

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The theory of resistive ballooning modes relevant to the banana-plateau collisionality regime is studied using the recently developed neoclassical MHD equations[1]. Employing the ballooning mode formulation and a multiple length scale analysis, a generalized set of poloidal flux surface averaged equations coupling the parallel ion flow velocity, $V_{\parallel}$, the vector potential, $A_{\parallel}$ and the electrostatic potential ϕ are derived. A particularly simple case in which the parallel sound wave coupling terms become negligible in the frequency range, $|\omega| \gg \omega_s$, where $\omega_s = s\, c_s/qr$, s is the shear parameter, c_s the sound speed and qr the connection length is dealt with. In this limit, the dispersion relation for a localized ballooning mode is obtained incorporating neoclassical effects such as the bootstrap current, enhanced polarization and pinch type currents. The calculations show that a new pressure-gradient driven instability with growth rates varying as $\mu_e^{1/2}$ (electron viscosity) is found. The enhanced polarization current is shown to reduce the growth rate of resistive ballooning modes in the classical regime. Further, our model highlights a smooth transition from the Pfirsch-Schluter to the (neoclassical) plateau and banana neoclassical collisionality regimes.

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A Tearing Mode Energy Principle for an Axisymmetric Plasma

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A stability functional, δW_{TG}, useful for determination of axisymmetric force-free plasmas is discussed. Unlike the well-known stability functional of Bernstein *et al.*, δW_{TG} includes stability against tearing modes. The functional is bi-linear in the perturbation of the vector potential and it is self-adjoint and gauge-invariant. The degree of singularity of the tearing mode eigenfunctions is minimized by a judicious choice of the gauge. If the minimum of δW_{TG} is positive, the plasma is stable. The Δ' concept, valid in simple geometries, is generalized to reflect variation of equilibrium quantities on the flux surface. The relationship of δW_{TG} to other functionals as well as its generalization to equilibria with pressure gradients is discussed.

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SHERWOOD THEORY MEETING 1988

The Kinetic Stabilization of Energetic Particle Internal Kink Mode and Fishbone Oscillations *

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Effects of the non-MHD behavior in the layer around the rational surface on the dynamics of the $m = n = 1$ internal kink driven by the presence of the energetic particle are studied. It is found that the usual branch, $\delta\widehat{W}_f + \delta\widehat{W}_k - i\sqrt{\omega(\omega - \omega_i^*)}/\omega_A = 0$ (supposedly responsible for the fishbone oscillations) is likely to be modified when the electron layer width (X_e) is smaller than the ion Larmor radius. However, there exists another branch with a mode width broader than X_e and the Alfvén layer width. A dispersion relation for this mode is derived and discussed. Detailed analytical and numerical studies, delineating the stabilizing effects on the MHD mode due to electrons resonance, are also presented.

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A Particle Method for Collisional Kinetic Equation*

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A new particle scheme fully deterministic, is devised for treating a kinetic equation with a collisional term. The equations of motion of the particles are the standard dynamic equations plus an additional term due to the collisions.

The method has been checked for the space homogeneous case in one and two dimensions for different collisional operators. A particular data structure (Voronoi diagram) has been used to handle a grid of moving particles in two dimensions.

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Helical Coil Driven Sawteeth*

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Sawteeth are widely believed to control plasma profile shapes. In addition, when sawteeth are not present, plasma impurities become peaked in the center. Helical coils may be used to generate sawteeth of arbitrary amplitude and period. Following [1], the reduced MHD equations with parallel and perpendicular heat conductivity are used to simulate helical coil driven sawteeth. Distinct cases emerge depending on the number of resonance surfaces. Profile modifications as a function the period of the driving coil, response time and necessary driving amplitude are given. Changes in the stability limits due to helical shaping are also discussed.

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TWO-SIDED DELAY EQUATIONS FOR QUASILINEAR BALLOONING MODE SATURATION

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ABSTRACT

Resistive ballooning modes saturate at finite amplitude by creating magnetic islands which cause the pressure gradient to decrease at the resonant surfaces. Using the equivalence of harmonics, the calculation of the saturated amplitude is reformulated as a nonlinear eigenvalue problem of a differential delay equation with the Connor-Hastie-Taylor formalism. Since the quasilinear equilibrium and stability problem is translation invariant to lowest order, the solution admits a quasimode expansion. The standard quasimode expansion is

$$A(\psi,\theta) = e^{-in\zeta} \sum_m e^{+i2\pi m\theta} \int_{-\infty}^{\infty} e^{-2\pi iy\left(m-nq_o(\psi)\right)} F(\psi,y)dy$$

Thus the operator $JB\cdot\nabla A$ is transformed to $\frac{\partial F}{\partial y} - inq_o\delta\nu(\psi,\chi)F$ where

$$\delta\nu = \nu - \nu_o = \left(\frac{R^2\delta p_q}{|\nabla\psi|^2}\right) + \left(1 + \frac{I_o^2}{|\nabla\psi|^2}\right)\frac{\delta I_q}{I_o} .$$

Finally we note that $e^{i\ell nq_o(\psi)}A(\psi,\chi)$ is transformed to $F(y-\ell)$. Thus $p'(\psi)A$ changes to $\sum_\ell p_\ell' F(y-\ell)$. Thus nearest equilibrium equations are transformed to

$$\frac{\partial\tilde{p}}{\partial y} - iq_o \sum_{\ell\neq 0} \left(\nu_1(y)\overline{\delta}q_\ell + \nu_2(y)\overline{\delta}p_\ell\right)\tilde{p}(y+\ell) = -iq_o \sum_\ell p_\ell' \tilde{A}(y-\ell)$$

$$\frac{\partial}{\partial y}\left(h(y)\tilde{A}(y)\right) - iq_o \sum \left(\nu_1(y)\overline{\delta}q_\ell + \nu_2(y)\delta p_2\right)h(y-\ell)A(y-\ell)$$

$$= -iq_o \sum_\ell \frac{\partial\sigma_\ell}{\partial\psi}\tilde{A}(y-\ell) - i(f_\zeta - q_o' yf\psi)\tilde{p} .$$

The island width is the nonlinear eigenvalue parameter contained implicitly in $p_\ell', q_\ell(w)$.

SHERWOOD THEORY MEETING 1988

Nonlinear Evolution of the $m = 1$ Quasi-Interchange Mode in Toroidal Geometry*

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Many features of the fast sawtooth crashes observed on JET can be accounted for by a low-shear $m = 1$ instability. The linear analysis of this mode, however, does not account for the abruptness of the transition from stability to a rapidly growing instability. We have evaluated the nonlinear corrections to the mode growth to lowest order in the amplitude, using a low-beta expansion of the Reduced Magnetohydrodynamic equations. These equations are shown to be identical to the full Magnetohydrodynamic equations in the linear regime except for the neglect of parallel kinetic energy and the effects of compressibility. The nonlinear forces are found to be stabilizing for the profiles so far investigated. These forces lead to the appearance of stable, finite amplitude bifurcated equilibria above marginal stability. In this respect our conclusions resemble those of Rutherford et al. for the zero-beta, free-boundary kink.[1]

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Waveguide FEL code results for ELF and MTX *

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The code WFEL[1] uses some of the pieces of the LLNL finite element free electron laser code FRED, such as particle loading and in particular the same space charge solution. The main electromagnetic field solver, however, is completely different, based on Wurtele's vacuum waveguide mode expansion, but with more accurate coefficients. This code in its rectangular guide version is complete and has been tested in a variety of ways. It can reproduce FRED results if we modify the coupling coefficients to match what FRED does (which is known to be an approximation for the TE–TM split).

When using the new coefficients (presumably the correct ones), the code predicts results different from those of FRED, but not grossly so. We have shown that the results of the wiggle field taper, in particular, are very insensitive to these changes in the coefficients, at least in the MTX 250 ghz case. Also, WFEL for 140 ghz tapered cases shows approximately the same peak powers as predicted by Jong using FRED. An explanation for the insensitivity of the taper results, despite clearly observable differences in the linear exponential regime, is threefold: a) the taper's effectiveness in focusing on the 01 mode, b) only a small reduction on the C_{01} at 250 ghz, c) the positive effect of a larger C_{21} causing a larger growth rate, somewhat compensating for the larger 21 relative power. Results would likely be more sensitive at 35 ghz, since then the new coefficients reduce the coupling of the TE_{01} mode.

Results from WFEL agree with those of Freund's (NRL) nonwiggle-averaged code, specifically on the ratio of the 01 and 21 mode power for ELF conditions (results somewhat different from FRED), and also on the ratio of the 21 power split into TM and TE modes (FRED says nothing about this). Both codes predict $TM_{21} << TE_{21}$ power for Elf conditions. This strongly disagrees with experiment[2] where the claim is comparable power in TM_{21} and TE_{21}. This glaring contradiction implies either that the experiment measured this property rather poorly, or that there remain inconsistencies in both computer codes.

Nearly complete is a version of WFEL applicable to both circular and elliptical waveguides, now less urgent since the new MTX plans are to first do 140 ghz experiments using rectangular waveguides.

We are discussing methods for improving the space charge algorithm with M. Caplan (LLNL), J. Wurtele (MIT), and H. Freund (NRL).

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ELECTROMAGNETIC TRAPPED-PARTICLE SIDEBAND INSTABILITY*

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Nonlinear effects have an important influence on intense pulsed electron cyclotron heating using free electron lasers (FEL). Relativistic effects allow resonant electrons to be nonlinearly trapped in large-amplitude coherent extraordinary and ordinary waves.[1] Trapping of the resonant electrons can reduce the opacity of the plasma and thus diminish the efficiency of the intended plasma heating or current drive. The trapping also alters the plasma dielectric so as to couple electromagnetic sidebands of the main wave. Our calculation demonstrates that this coupling destabilizes the sidebands in the same way that trapped particles produce sideband instabilities in Langmuir waves[2] and whistlers.[3] For weakly coupled electromagnetic sidebands, the most unstable modes are separated in frequency from the main wave by the trapping frequency and are forward scattered. If the sidebands grow to large amplitude, the trapped electrons can be decorrelated from the main wave leading to the saturation of the sideband instability and a possible improvement in the opacity of the plasma.

Our calculation is motivated by experiments to be conducted in the Microwave Tokamak Experiment (MTX) at Livermore. We consider an ordinary wave and solve the nonlinear Vlasov-Maxwell equations. The nonlinear coupling is due to $\underline{V} \times \underline{B}$ effects leading to a nonlinearly perturbed electron Larmor radius and an associated perturbed current. The coupling and resulting growth rates are weak for MTX parameters, and the growth of the unstable sidebands will be limited by the pulse length of the FEL.

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MAGNETIC ISLAND FORMATION IN THREE-DIMENSIONAL PLASMA EQUILIBRIA

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The formation of magnetic islands due to finite plasma pressure in three-dimensional equilibria is investigated. This problem has been analyzed previously in Refs. 1 and 2 beginning with a vacuum field which has good flux surfaces. A linearization technique is used in Ref. 2 to find the plasma current from the equilibrium equations far from a resonant surface ("exterior region"). We implement a boundary-layer analysis that avoids the low-beta approximation in the exterior region, and solve for the plasma current exactly from the equilibrium equations. The singularity in the current is resolved by solving the equilibrium equation in the neighborhood of the rational surface ("inner region") using a technique similar to the problem of saturated resistive instabilities in two-dimensional plasmas.[3] The Δ' parameter of tearing mode theory is used to match the inner and outer regions. This yields, as anticipated,[2] an island width which depends on the resistive interchange criterion due to Glasser, Greene and Johnson.[4] The modifications of the equilibrium due to the interaction of the vacuum magnetic helicities in the presence of non-vanishing plasma pressure are calculated by an iterative procedure. Estimates of the island sizes for different stellarator experiments will be presented.

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Extended Neoclassical MHD Equations*

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The neoclassical MHD equations[1] are extended to include temperature gradients and heat flow effects. These equations are time evolution equations for the density, temperature, perpendicular and parallel mass flows ($\rho_m \vec{V}_m \equiv \sum_i n_i m_i \vec{V}_i$), perpendicular and parallel ion heat flows, perpendicular electron heat flow and finally the magnetic flux. These equations are valid on a time scale $\nu_i \lesssim \partial/\partial t \ll \nu_e$ and in all collisionality regimes (banana, plateau and Pfirsch-Schlüter). They generalize the "Braginskii equations"[2] in the sense that the effects of time-dependent heat flows ($\partial \vec{q}/\partial t$), and parallel and gyroviscous stress tensors ($\mathbf{\Pi}_{\parallel,\wedge}, \mathbf{\Theta}_{\parallel,\wedge}$) are included systematically for all collisionality regimes through the 18-moment method[3] ($n, T; \vec{V}, \vec{q}; \mathbf{\Pi}, \mathbf{\Theta}$). Effects of trapped particles in all collisionality regimes are taken into account through the multi-collisionality-regime parallel viscous stress forces [3], $\vec{\nabla} \cdot \mathbf{\Pi}, \vec{\nabla} \cdot \mathbf{\Theta}$. The FLR (finite Larmor radius) effects are rigorously considered through the gyroviscous stress force ($\vec{\nabla} \cdot \mathbf{\Pi}_\wedge$) in the momentum balance equation and the "gyro-" heat stress force ($\vec{\nabla} \cdot \mathbf{\Theta}_\wedge$) in the heat flow balance equation.

We employ these extended neoclassical MHD equations to analyze the η_i instability. We will discuss the importance of the heat "polarization" flow ($\partial \vec{q}_i/\partial t$) in the heat flow equation and the FLR effects due to the gyroviscous stress tensors.

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Free Energy and Entropy Evolution in Collisional, Magnetized Plasmas and Neoclassical MHD*

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In the moment approach[1,2] to deriving Braginskii[3] type equations and neoclassical MHD equations[4] the distribution function is expanded about a Maxwellian in terms of the particle ($\vec{u}_0 = \vec{V}$) and heat ($\vec{u}_1 = -2\vec{q}/5p$) flows, and the viscous ($\mathbf{\Pi}$) and heat viscous ($\mathbf{\Theta}$) stresses. These distortions of the distribution function are all first order in the small Larmor radius expansion. In this work we utilize this expansion of the distribution function and the moment equations for the evolution of $n, T, \vec{V}$, and $\vec{q}$ to determine the entropy, free energy[5] and entropy evolution equation correct through second order in the small gyroradius expansion. The dominant source of free energy for localized instabilities ($\Delta \lesssim \rho_i$) is surprisingly not directly the usually considered expansion free energy. Rather, it is that due to the neoclassical flows in the plasma which in turn depend strongly on the radial ion temperature gradient. Possible implications of this for fluctuation levels and anomalous transport in tokamaks will be discussed.

The second order entropy balance equation is derived from the fundamental principles of thermodynamics. It is given by

$$\partial S/\partial t + \vec{\nabla} \cdot \vec{J}_S = \Phi_S,$$

$$\text{where} \quad S = S_0 + S_2, \quad S_0 = -n \ln\left[n\left(\frac{m}{2\pi T}\right)^{3/2}\right] + \frac{3}{2}n, \quad S_2 = -\frac{nu_0^2}{v_T^2} - \frac{5nu_1^2}{2v_T^2},$$

$$\vec{J}_S = S\vec{V} + \vec{q}/T - (\vec{u}_0 \cdot \mathbf{\Pi} + \vec{u}_1 \cdot \mathbf{\Theta})/T,$$

$$T\Phi_S = -\left\{\vec{u}_0 \cdot \vec{F}_0 + \mathbf{\Pi} : \vec{\nabla}\vec{u}_0 + \vec{u}_1 \cdot \vec{F}_1 + \mathbf{\Theta} : \vec{\nabla}\vec{u}_1\right\},$$

in which $\vec{F}_0 \equiv \int d^3v\, m\vec{v}C(f)$ and $\vec{F}_1 \equiv \int d^3v\, m\vec{v}(5/2 - mv^2/2T)C(f)$ are the friction and heat friction forces. Dissipative processes in the neoclassical MHD equations can be clearly identified through this entropy production rate Φ_S. Both of the gyroviscous stress tensors, $\mathbf{\Pi}_\wedge$ and $\mathbf{\Theta}_\wedge$, are shown to be dissipationless.

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Degradation of Energy Confinement in Tokamaks Due to Rotational-Gyroviscous Effects

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In a strongly rotating ($v_\phi \sim v_{th}$) tokamak plasma, energy is transported radially outward as a result of the work done by the rotating plasma against t pressure tensor, in particular the gyroviscous stress. We define the ene confinement time as

$$\frac{1}{\tau_E} \equiv \frac{\int \frac{\partial}{\partial 1_\psi} \langle RB_p Q_\psi \rangle dV}{\int \frac{3}{2} \langle RB_p nT \rangle dV} = \frac{\int \frac{\partial}{\partial 1_\psi} \langle RB_p (\frac{5}{2} pv_\psi + q_\psi) \rangle dV}{\int \frac{3}{2} \langle RB_p nT \rangle dV} + \frac{\int \frac{\partial}{\partial 1_\psi} \langle RB_p v_\phi \pi_{\phi\psi} \rangle dV}{\int \frac{3}{2} \langle RB_p nT \rangle dV}$$

$$\equiv \frac{1}{\tau_E^o} + \frac{1}{\tau_E^\omega},$$

where the first term represents all conductive and convective (includ anomalous) processes and the second term represents the gyroviscous contribution. Using the form for $\pi_{\phi\psi}$ given in Ref. [1], this may be written

$$\tau_E = \tau_E^o \left[1 + \Omega^2 \tau_E^o fp/\omega \right]^{-1},$$

where $\Omega \equiv v_\phi(0)/R$ is the angular rotation frequency, $\omega \equiv ZeB/m$ is the gyrofrequency, and $f_p = (1 + \alpha_n + \alpha_T)/(1 + \alpha_T + \alpha_n + 2\alpha v)$ is a profile factor resulting from the assumption that the radial distributions of n, T and v_ϕ c be represented as parabolas raised to the power α.

Comparison of this expression with the measured [2] energy confinement t in a beam power scan series of discharges in TFTR yields excellent agreem [3].

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3C16

Adiabatic Evolution of a Kinetic FRC * R. B. WEBSTER†, J. L. SCHWARZMEIER‡, H. R. LEWIS, C. K. CHOI†, *Los Alamos National Laboratory, Los Alamos, NM 87545.*— Kinetic effects are thought to play an important role in determining the stability and confinement properties of a Field Reversed Configuration (FRC). In cylindrical geometry, we present a transport model that solves for the evolution of collisionless equilibrium distribution functions $f_{s0}(H, p_\theta)$ that results from slowly varying boundary conditions. The assumed form of the distribution functions yields macroscopic equilibrium profiles that model well the profiles of a long, nearly collisionless FRC, allowing for non-isothermal ions and finite temperature electrons. Effects of finite length are included by imposing net axial force balance. We use a trial function approach. Given an initial equilibrium state we vary the distribution functions for both the ions and the electrons at the end of a time step in such a way that the L_2 error of the orbit averaged Vlasov equations is minimized. The fields are found by assuming that the plasma is always in a collisionless quasineutral equilibrium state. The averaging has been found to be necessary to give physically reasonable results. In spite of the assumption that there are no collisions, bulk plasma rotation and gyroviscous effects are automatically included. In this work, we have modified the usual 1-1/2 D transport formulation to obtain a convergent algorithm to obtain self consistent evolution.

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LONG WAVELENGTH COLLISIONAL ION TEMPERATURE GRADIENT MODES*

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Recent numerical studies of the transport resulting from fluctuations driven by the electron temperature gradient have indicated that the transport level depends sensitively on the longest wavelength fluctuation which can be excited.[1] In the case of electron temperature gradient driven modes the longest wavelength which can be excited is determined by electromagnetic effects. We consider the ion temperature gradient driven, or ion mixing mode, which is qualitatively similar to the electron mode but is not stabilized at long wavelength by electromagnetic effects. Here, at long wavelength and low frequency collisional effects such as viscosity and thermal conductivity are important.[2] We consider this mode in toroidal geometry where the appropriate cross-field transport is given by neoclassical theory. In addition, magnetic pumping is found to affect the stability bounds of the mode. Stability at long wavelength is determined essentially by two parameters: the logarithmic temperature gradient and the collisionality.

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SHERWOOD THEORY MEETING 1988

Self-Similar Evolution in the Nonlinear Stage of the Undular (Ballooning) Instability *

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The undular perturbation ($\boldsymbol{k}||\boldsymbol{B}$) can be unstable due to the magnetic buoyancy. We have found through a simulation and theoretical study that there is a new type of self-similar solution of ideal MHD in the nonlinear stage of the undular mode ($\boldsymbol{k}||\boldsymbol{B}$) of magnetic buoyancy instability. This instability is known as 'Parker instability' in astrophysics, and is more familiarly known as ballooning instability in fusion plasma physics. A two dimensional MHD code is used to study the nonlinear evolution of the instability in isolated horizontal magnetic flux imbedded in a gravitationally stratified isothermal plasma with exponential density (pressure) distribution. The horizontal flux sheet is initially located so as to satisfy magnetostatic equilibrium under a constant gravitational acceleration. As the instability develops, the gas slides down the expanding loop, and the evacuated loop rises due to enhanced magnetic buoyancy. In the nonlinear regime of the instability, both the rise velocity of a magnetic loop and the local Alfvén speed at the top of the loop increase linearly with distance and show self-similar behavior with distance when the wavelength of the initial perturbation is much smaller than the horizontal size of the computing domain. We have studied this self-similar expanding motion of the magnetic loop analytically, and found that there is a quasi-one-dimensional similarity solution for the vertical variation of physical quantities at the midpoint of the magnetic loop, which agrees well with simulation results. The solution has the characteristics that the fluid velocity and the Alfvén speed on each magnetic loop (in Lagrangian frame) increase exponentially with time and become infinite at infinity because the loop is evacuated by the sliding motion of matter due to the gravitational pull. Applications to solar atmosphere, etc. will also be discussed.

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Generation of Potentials in the Mirrortron*

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The "Mirrortron" is a device in which mirror physics principles are employed to generate localized regions of transient electric fields for possible application to a kind of plasma-based linear accelerator for heavy ions. In a mirror cell containing a low density plasma of cold ions and relativistic electrons having a loss-cone type of distribution function a local mirror field located midway between the end mirrors is pulsed on in 10 to 20 nanoseconds. The pulsed mirror begins to expel electrons, while the plasma ions remain essentially motionless. Quasi-neutrality steps in to create a local positive space-charge potential. From mirror theory it can be shown that the equipotentials correspond to constant-B contours in the magnetic field, thus providing an external means for controlling the focusing character of the accelerating electric field. The theory for this effect and for other properties of the mirrortron will be presented.

Reference: R.F. Post, "Generation and Control of High Transient Electrical Potentials within a Mirror-Confined Plasma," Physical Review Letters, 58, (1987) 878.

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ABSTRACT WAS WITHDRAWN

Reactor Relevant Fast Wave Current Drive Regimes in Tokamaks

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The efficiency of current drive by fast waves in tokamaks as estimated by the Karney-Fisch formula can be quite attractive for reactors. Furthermore, fast waves do not suffer from the density limits imposed by accessibility on slow waves. It is thus of interest to see what frequency ranges of fast waves are relevant to reactors when limitations due to wave and energetic particle physics are taken into account.

In this paper, we consider mode conversion to slow waves and Bernstein waves, competition of absorption between electrons, bulk ions and α-particles, and the effect of trapped particles on current drive efficiencies. When these effects are taken into account, one finds that there are two regimes, $\Omega_i < \omega < 2\Omega_i$ and $10\,\Omega_i \lesssim \omega < \omega_{LH}$ in which one may expect reasonable current drive efficiencies at reactor-like densities and temperatures.

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A BASIC ANALYTIC MODEL FOR DIVERTOR AND SCRAPE-OFF IN TOKAMAKS

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A basic analytic model for the divertor and main plasma scrape-off region in tokamak is developed. The Two Chamber Model (TCM) of Langer and Singer [1] is employed. The geometric mean flux-limited formula for parallel electron heat flux is used. Method for analytic solutions of TCM is developed. Analytic solutions show discontinuous changes in plasma parameters for continuous changes in other parameters. Results of analytic model are discussed. Directions for improvements in TCM for more realistic modelling are pointed out.

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Effects of Inverted Density Profiles and Impurity Concentration Gradients on Confinement in H-mode Discharges

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A major puzzle in current fusion physics is the explanation of the apparently good bulk confinement properties of H-mode discharges, with flat or somewhat inverted (electron) density profiles. Reasonable assumptions concerning fast ion deposition profiles then suggest that the ion density profile is even more hollow. Thus, we are naturally motivated to explore anomalous transport due to microinstabilities in plasmas with inverted density profiles. In particular, we consider the toroidal η_i-mode and the dissipative trapped-electron mode.

Instability of toroidal η_i-modes occurs for higher values of $|\eta_i|$ than in the case of centrally peaked ion density profiles. Since large transport occurs for $|\eta_i| \gg \eta_{cr}$, this indicates that the $T_i(r)$ profile is largely determined by considerations of 'marginal stability' and that more peaked ion temperature profiles (i.e. decreased ion thermal transport) should result in inverted density gradient plasmas. The character of the slab η_i-mode with inverted profiles and the effects of impurities are also being investigated and will be discussed. For the electron drift modes of relevance (i.e. the dissipative and collisionless trapped electron modes), density profile inversion (i.e. $\eta_e < 0$) is also strongly stabilizing, although subdominant circulating electron destabilization effects are weakly enhanced.

Quantitative comparisons with confinement data from H-mode plasmas are being pursued and will be discussed.

CURRENT DRIVE FOR A HIGH-BETA REACTOR*

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ABSTRACT

One of the major problems with driving current with rf waves in a high-beta reactor is in getting the waves to penetrate the higher densities found in such a reactor. In particular, it has been found difficult to find a ray spectrum that will drive current in the second-stability reactor developed at Argonne as part of the Tokamak Power Systems Study (TPSS) using the same approach as for first-region reactors.[1] This approach uses lower-hybrid waves to drive current near the edge and higher frequency (~ 1 GHz) fast waves to provide current near the center. Fast waves of this frequency do not penetrate sufficiently for the higher-density TPSS reactor. Low frequency (< 100 MHz) ion-cyclotron-resonant-frequency (ICRF) waves, on the other hand, achieve greater penetration because of their large radial group velocity and ability to propagate over a wide range of refractive index.[2] In addition, they do not couple to slow waves. By careful selection of the wave frequency, it is possible to damp these waves on electrons, via transit-time magnetic pumping, while avoiding ion-cyclotron resonant damping. The current-drive efficiency of these waves is theoretically as good as that obtained with lower-hybrid waves, and experiments are bearing this out. This paper describes the use of low-frequency ICRF waves to drive the current in the TPSS reactor. The topological change of the ion-cyclotron resonant surfaces because of the high internal magnetic fields is substantial and is also discussed.

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MHD Simulation of Tokamak Fueling by the Injection of Compact Toroids(*)

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It has been recently suggested that a tokamak reactor can be fueled through the injection of compact toroids (CT's)[1]. It is believed that such a technique is necessary since conventional fueling methods are expected to be inadequate for deep penetration. One of the critical issues with such a scheme is magnetic reconnection, for it plays a major role in determining where and when the fuel is deposited.

We model this injection scheme using the nonlinear, compressible, resistive MHD initial-value code TEMCO[2]. Rather than treat this very complicated problem in its fullest, we assume that the compact toroid is initially placed at rest in a uniform magnetic field modified to exclude the spherical CT. The symmetry axis of the CT is initially at right angles to the external field direction. The simulation shows that the CT tilts 90 degrees in about an Alfven time, its magnetic moment lining up with the tokamak magnetic field. The subsequent magnetic evolution is then observed.

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FULL-WAVE CALCULATIONS IN FLUX COORDINATES FOR TOROIDAL GEOMETRY*

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A new 2-D full-wave code, HYPERION, employing a poloidal and toroidal mode expansion and including the toroidal terms arising in the wave equation has been developed. It is based on the existing modules developed for the MHD stability codes and uses as input the tokamak equilibria calculated with the RSTEQ code.[1] At present the plasma response is described by the collisionally broadened cold plasma conductivity. However, the code is written in straight field line coordinates, which permits the accurate representation of $k_{\parallel}$ and as a consequence allows the incorporation of the plasma Z functions. This code also retains the $E_{\parallel}$ component of the electric field which will allow the study of the low density region of the plasma.

We have done detailed benchmarking of the HYPERION code in the cold plasma limit with the existing finite difference ORION[2] full-wave code. The agreement is very good. Results of the benchmarking and the effect of the toroidal terms will be presented at the meeting.

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On the Bifurcation of Periodic Traveling Waves in the Equations of Collisionless Plasma Kinetic Theory

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The one-dimensional, multi-species Vlasov-Poisson-Amperé equations, and the more widely studied Vlasov-Poisson equations, do indeed possess the periodic traveling wave solutions first sought by Simon and Rosenbluth[1]. These traveling waves arise in bifurcating branches of solutions which intersect the infinite dimensional manifold of spatially uniform Vlasov equilibria; a branch whose members have wavelength $2\pi/k$ intersects this manifold at an equilibrium which is "marginally stable" to disturbances of this wavelength. The attempts by Simon and Rosenbluth[1] and by Burnap *et al.*[2] to calculate approximate expressions for these waves are plagued by singularities which make the interpretation of the expansions problematical. Moreover, these singularities certainly are not conducive to a proof of convergence or existence. While these authors have constructed their perturbation theories based on the linearized Vlasov-Poisson operator—whose continuous spectrum, which occupies the entire imaginary axis, is the source of the aforementioned singularities—we have taken a different approach. By first proving that non-trivial periodic traveling wave solutions must be BGK modes,[3] such as those which represent the distribution functions in the wave frame as

$$f_\alpha(x,u) = \begin{cases} g_\alpha^+\left(\dfrac{u^2}{2} + \dfrac{q_\alpha}{m_\alpha}\phi(x)\right), & u \geq 0 \\ g_\alpha^-\left(\dfrac{u^2}{2} + \dfrac{q_\alpha}{m_\alpha}\phi(x)\right), & u \geq 0 \end{cases}$$

where $g_\alpha^\pm$ are unknown functions, we reduce the problem to a nonlinear Poisson equation for the electric potential:

$$\frac{d^2\phi}{dx^2} + 4\pi \sum_\alpha q_\alpha \int_0^\infty \left[g_\alpha^+\left(\frac{u^2}{2} + \frac{q_\alpha}{m_\alpha}\phi(x)\right) + g_\alpha^-\left(\frac{u^2}{2} + \frac{q_\alpha}{m_\alpha}\phi(x)\right)\right] du \, .$$

subject to certain nonlinear constraints. The linearization of the corresponding nonlinear operator about zero potential is extremely well behaved, and by using the functions $g_\alpha^\pm$ as a bifurcation parameter we are able to establish the existence of a bifurcation to non-trivial periodic solutions in the nonlinear Poisson equation. The smoothness of the solutions allows an asymptotic amplitude expansion to be developed for these bifurcating branches. Once the bifurcation behavior of the nonlinear Poisson equation is established, the bifurcating families of periodic traveling waves for the Vlasov-Poisson-Amperé and Vlasov-Poisson equations also are easily understood. Asymptotic expansions which approximate these solutions have been developed.

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USE OF 2-D CODES FOR STABILITY STUDIES OF 3-D CONFIGURATIONS

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The periodicity associated with having a finite number of helical field periods in a typical stellarator makes fully three dimensional studies of equilibrium configurations feasible.[1,2] Although stability studies with respect to modes that do not possess this periodicity can be done, they are difficult. Application of two dimensional codes which use averaging over the helical fields would therefore be useful. Results obtained with such codes have been shown to agree well with those from fully three dimensional ones.[3] The major physics restrictions on the modes that are found in the two dimensional studies, the suppression of the fast magnetosonic modes and the decoupling of modes with different toroidal mode numbers, should also be obtained in the general configurations. Thus it is useful to investigate how to manipulate the output from 3-D codes like BETA[1] and VMEC[2] into a form where it could be used as input for 2-D codes like STEP[4]. We describe some improvements we have recently made on the STEP code and show how these considerations lead naturally to such an extension.

* Supported by the U.S. Department of Energy.

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Theoretical Particle and Energy Flux Formulas for Tokamaks

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Using the notation of Ross *et al.* [1], a set of particle and energy flux formulas has been assembled which should be comprehensive and complete enough to support extensive transport studies. The collection includes fluxes due to neoclassical effects, trapped electron/η_i modes, rippling modes, resistive ballooning, kinetic ballooning, η_e modes, and post-sawtooth stochastic flux surfaces. A number of modifications of published formulas were used to produce a formula set usable over a wide parameter range. These modifications include (1) cutoff of drift wave fluxes at high β, (2) a nonlinear saturation enhancement of diamagnetic-drift-stabilized resistive ballooning fluxes, (3) cutoff of kinetic ballooning fluxes in the second stability region, and (4) restricting use of published η_e mode formulas to low collisionality and moderate values of η_e. Correction factors are also included to prevent singularities in large gyroradius and very low shear regimes. With the exception of the option for temporary enhancement of transport for a brief period immediately after sawteeth, the formulas depend only on local plasma parameters and have no *a priori* empirical content. They form, therefore, an appropriate basis for rigorous statistical tests of their predictions against plasma profile and global confinement data bases.

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IGNITION BY NEUTRONLESS FUSION REACTIONS*

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Experiments capable of exploring the fusion burn conditions of $D\text{-}He^3$ mixtures and based on present-day technology can be envisioned[1] and designed. This follows from the possibility of producing stable[2] plasma equilibrium configurations, confined by high magnetic fields, where $\beta = 8\pi\langle p\rangle/B^2$ is finite ($\beta \simeq 8$ to 10%). By now the design of "compact" toroidal experiments has progressed[3] to the point where plasma currents I_p exceeding 10 megamperes can be produced while the average fields $\bar{\bar{B}}_p$ associated with these currents can be as high as 4 tesla. In this case $D\text{-}He^3$ ignition can be achieved for $\beta_p \equiv 8\pi \langle p\rangle/\bar{\bar{B}}_p^2 \sim 1$. In fact, the plasma regimes of interest involve strongly peaked temperature profiles, with $T_{Max} \simeq 65$ keV, and T_o, peak electron densities up to about 2×10^{15} cm^{-3} that correspond to values of the "central beta", $8\pi p_o/B_o^2$, about 0.45 for $B_o \simeq 13$ tesla. We note that synchrotron emission involves a limited fraction of the overall energy balance and that lower ignition temperatures are found if the fusing nuclei are spin polarized. Given the values of β_p that are compatible with a 50/50 mixture of $D\text{-}He^3$, it is possible to envision the burning of richer mixtures in helium 3, that require higher electron densities, in order to minimize the neutrons produced by D-D reactions.

The optimization of the equilibrium configuration and the relevant poloidal field system has been made possible by recently developed numerical MHD codes.[4] The reference plasma parameters that have been chosen for our analyses of both technical feasibility and transport, concerning the sequence of physical processes that can lead to ignition, are: R_o[major radius] $\simeq 1.7$ m, a[minor radius] $\simeq 0.65$ m, κ[elongation] $\simeq 1.8$, $B_T \simeq 13.5$ T, $I_p \lesssim 18$ MA, $\bar{\bar{B}}_p \equiv 0.4\, I_p/(a+b) \lesssim 4$ T.

In order to minimize the time needed to achieve $D\text{-}He^3$ ignition, the start-up is envisioned[5] to involve the burning of tritium. Even in this case the needed magnet systems have to be compatible with longer current pulses than those adopted for D-T ignition experiments. Therefore new coupled central solenoid-toroidal magnet configurations, where the rate of ohmic heating has been minimized, have been considered.

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BOOTSTRAP CURRENT ENHANCEMENT IN TOKAMAKS*

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The presence of bootstrap currents could reduce the current drive requirements of tokamak reactors. Therefore, it is desirable to determine how to increase the amount of bootstrap current that can occur in tokamaks. We find that the magnitude of the bootstrap current can be enhanced by increasing the fraction of trapped particles in medium-aspect-ratio ($A \sim 5$) tokamaks. To increase the fraction of the trapped particles one can introduce cos 2θ and/or cos 3θ harmonics whose amplitudes are comparable to the inverse aspect ratio in the magnetic field spectrum $B/B_0 = 1 + \sum_n \epsilon_n \cos n\theta$. These additional harmonics could be obtained by strongly shaping the flux surfaces. An analytic expression for the bootstrap current will be given and several quantitative examples will be presented.

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PROPAGATION OF MODE-CONVERTED ION-BERNSTEIN WAVES IN TOROIDAL PLASMAS+

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ABSTRACT

The usual geometric optics ray trajectory equations for weak damping rely on the assumption that the anti-hermitian component of the conductivity tensor describing the plasma is much larger than the hermitian part of the tensor. The ray equations become significantly modified if this does not hold while the weak damping limit may still prevail [1]. We find that this is indeed the case when studying the propagation of ion-Bernstein waves in a toroidal plasma. The ion-Bernstein waves we have been interested in are those that arise from the mode-conversion of the fast Alfveń wave in ICRF. Our results showed that the ion-Bernstein wave can Landau damp onto the electrons by upshifting the magnitude of the poloidal wave numbers as the rays propagate in a toroidal plasma [2,3]. In our recent numerical analysis we have modified the ray equations so that they will remain valid for an arbitrary conductivity tensor. We will present results from this more general analysis and compare them with our results obtained from the conventional ray-tracing equations.

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Kinetic Effects on the FRC Tilt

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The stability of the internal tilt mode in an FRC is significantly altered from MHD predictions by kinetic ion effects. A variational form of the linearized Vlasov-fluid model (collisionless ions, massless fluid electrons) is used to compute self-consistent eigenfrequencies and eigenfunctions for the kinetic tilt mode.[1] Displacements are presently restricted to be constant on a flux surface and to have no radial component.[2] This is the rigid-axial-shift approximation for the displacement field. Calculations have been done to determine how kinetic stabilization changes with plasma elongation. Three equilibria of different elongations with the same pressure profile were used in this study. Work is in progress to determine the stability of large s plasmas with a hot ion component added to the thermal component. Plans to remove the rigid-axial-shift ansatz are now being formulated.

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SHERWOOD THEORY MEETING 1988

Toroidal Electron Temperature Gradient Driven Turbulence *

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In order to explain the anomalous transport of electrons in tokamaks, we propose a set of reduced nonlinear equations that describe the coupling of linearly unstable short wavelength ρ_e electrostatic fluctuations driven by the electron temperature gradient η_e to the longer wavelength c/ω_{p_e} electromagnetic fluctuations. The instability is the toroidal version of the η_e driven lower hybrid drift mode in the presence of the electron temperature gradient emphasized by Guzdar[1] and Lee[2] for a slab. The growth rate $\gamma \sim v_e/(r_{T_e}R)^{1/2}$ is driven by the local bad curvature and the electron temperature gradient. Since the system of the reduced equations is weakly 3D, with $\nabla_\perp \gg \nabla_\| = \partial_z - \frac{1}{B}[\tilde{A}_\|, \;]$, we may consider the possibility of an inverse cascade $\rho_e \rightarrow c/\omega_{p_e}$ in the energy spectrum, as in the 2D Navier-Stokes turbulence. Such an inverse cascade may explain the free-energy source of the magnetic fluctuations $\tilde{A}_\|$. Previously, such magnetic fluctuations have been assumed, and then used to explain the neo-Alcator and Merezhkin-Mukhovatov type of scaling for χ_e.

The similations show a finite χ_e in the limit of a flat density gradient ($\eta_e \gg 1$) in contrast to the previously[1,2] given χ_e. Simplified, large η_e nonlinear equations are derived and solved numerically for the interior H-mode plasma profiles. The anomalous heat flux is composed of an electrostatic convection $q_e = \langle v_x p_e \rangle$ and an electromagnetic component. While the electrostatic component can be understood from the mixing length theory, the electromagnetic component of the heat flux is more difficult to estimate.

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EFFECT OF COMPRESSIBILITY ON RESISTIVE INTERCHANGE MODE STABILITY FOR STELLARATORS AND TORSATRONS

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Parallel compressibility effects on the stability properties of resistive low-n internal modes for Heliotron-E and torsatron configurations are being studied. A version of the FAR code,[1] where the stellarator terms coming from average equations are incorporated and which also includes parallel or sound compressibility, is used.[2]

Comparison of compressible cases with incompressible ones shows that compressibility reduces the growth rate of the low-n resistive interchange modes close to the resistive stability threshold. Both compressible and incompressible results have also been compared with the stability limit mapped from the resistive D_R criterion[3] applied to the equilibria calculated with the VMEC code.[4]

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ENERGETIC PARTICLE STABILIZATION OF INTERNAL KINK MODES IN TOKAMAKS*

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Energetic particle effects on the m=n=1 internal kink are studied by the NOVA-K code[1] which numerically computes the kinetic-MHD stabilities of axisymmetric toroidal plasmas in realistic numerical tokamak equilibria. For ideally unstable plasmas, our results show that for $\gamma_{MHD} > \langle\omega_d\rangle$, the hot particle is stabilizing for small β_h, but becomes destabilizing as β_h becomes larger. For $\gamma_{MHD} \leq \langle\omega_d\rangle$, the ideal internal kink is stabilized as β_h reaches β_{hc}. But, for $\beta_h > \beta_{hc}$, a weaker instability (fishbone mode) is excited due to the magnetic drift resonance. For ideally stable plasmas, the eigenfuction is singular near q = 1 surface, and thus $\beta > \beta_{crit}$ (ideal MHD) is a necessary condition for the resonant instabilities.

A new analytical dispersion relation has been derived variationally by including the toroidal curvature effects in the q=1 layer. In the ideal MHD limit, the growth rate is proportional to $(\beta-\beta_{crit})^{1/2}$ near the marginal stability. The analytical solutions can explain the basic features of the numerical solutions obtained from the NOVA-K code and provide a new scenario of the experimentally observed fishbone activities in the neutral beam injection experiments.

*Supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO3073.

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THE NUCLEAR DYNAMO

Can a Nuclear Tornado Annihilate Nations?

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Summary

The author has been concerned about nuclear weapons safety since 1952 when he heard Yale Professor Gregory Breit give a Secret lecture on ignition of the atmosphere by a runaway nuclear weapon explosion. After twenty-five years of nuclear fusion research, the author developed the hypothesis of a nuclear dynamo for a controlled nuclear fusion reactor. This dynamo hypothesis suggests properties for a nuclear tornado which might annihilate various nations if accidentally triggered by one high yield to weight nuclear weapon detonation. The present article discusses the previously classified reports on ignition of the atmosphere, the properties of a nuclear dynamo, methods to achieve a nuclear dynamo in the laboratory, the properties of fusion chain reactions, and the analogy of a nuclear dynamo to a nuclear tornado. The author urges an unclassified, international study of this question.

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Interaction of Energetic Ring-Current Protons with Magnetospheric Hydromagnetic Waves[a]

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Recently it has been shown[b] that the magnetic drift-bounce resonance of hot ($E \sim 100$ keV) storm-time ring-current protons can destabilize magnetohydrodynamic (MHD) waves in the earth's magnetosphere. The unstable eigenmodes are antisymmetric along $\mathbf{B}$ and have large azimuthal wave numbers $k\rho \sim 0.5$, where ρ is the proton Larmor radius. We investigate the non-self-consistent effect of the modes on the particles using magnetic coordinates and Hamiltonian guiding center equations for particle motion in a dipole field subject to time-dependent MHD wave perturbations. The equations of motion are solved numerically to examine induced particle diffusion caused by magnetic drift-bounce resonances. We present results for drift resonances of equatorially mirroring protons and discuss extensions to include finite Larmor radius effects.

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[a]Supported by NSF Contract No. ATM-86-09585
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BALLOONING STABILITY OF A TOROIDALLY ROTATING PLASMA

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Abstract

The stability of high (m,n) ideal ballooning modes in a toroidal plasma rotating rigidly about its axis of symmetry is investigated. Centrifugal forces induce a poloidal asymmetry in the plasma density and also cause a separation of the constant pressure surfaces from the magnetic flux surfaces. This has a favourable influence on the Shafranov shift and leads to stabilisation of the ballooning modes in all but the outer regions of the plasma (i.e. for $r < L_p$, where L_p is the pressure scale length). The stabilisation can occur for rather modest values of the parameter $\delta = \epsilon V_o^2/C_s^2 << 1$, where V_o is the flow velocity, C_s is the sound velocity and $\epsilon = r/R$ is the inverse aspect ratio). Our results are relevant for neutral beam heated tokamak plasmas where plasma rotations of the order of the sound velocity have already been reported in several experiments (e.g. ISX[1], PDX[2], TFTR[3] and JET[4]. The $s - \alpha$ diagram obtained from our analysis also indicates that plasma rotation can be of help in gaining access to the second stability regime in high beta experiments.

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FAST SOLUTIONS TO THE GRAD-SHAFRANOV EQUATIONS

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In the last few years, the use of multigrid [1] techniques for obtaining solutions to non-linear elliptic equations has been recognized (in fields other than numerical analysis) as both fast and robust . By making use of a sequence of coarser grids in the solution process, multigrid obtains the solution (to truncation error) on the finest grid in the work equivalent of a few relaxation sweeps on the finest grid. Because the interplay of grids in the solution process forces the evolving numerical solution to remain 'close' to the actual solution during all stages of the process, solutions to non-linear problems are obtained as fast as solutions to linear problems. In addition, this interplay allows almost all non-linearities to be treated with equal ease and avoids the usual homotopies needed to reach difficult regions of parameter space.

We have developed a flux-coordinate equilibrium solver for the Grad-Shafranov equation (with and without toroidal flow) using a multigrid technique. The orders of magnitude decrease in computational time permits extensive equilibrium parameter optimization with modest computer resources. The possibility of real time diagnostics using this method is investigated. Comparisons and examples will be presented.

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VARIATIONAL FORMULATION FOR A MULTI-FLUID FLOWING PLASMA WITH APPLICATION TO THE INTERNAL TILT MODE OF A FIELD-REVERSED CONFIGURATION

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The previous formulation of the internal tilt stability of a rigidly-rotating, two-fluid field-reversed configuration (FRC)[1] has been extended to account for an arbitrary number of massive fluids, and arbitrary equilibrium flows. Thus the formalism includes, e.g. (1) toroidal and poloidal rotations; (2) velocity shear; and (3) terms from the generalized Ohm's law (e.g. Hall current, electron pressure, and finite electron mass).

The theory is applied to the internal tilt mode of an FRC for the reduced case of two fluids (massless electrons), a rigidly rotating Hill's vortex-like equilibrium, and the internal tilting mode (disturbance boundary at the separatrix). Rotation can stabilize the internal mode but only for relatively large rotation rate (rotation speed comparable to the Alfven speed), as was reported by Clemente and Milovich[2]. A new stability regime appeared as a result of the Hall effect. The Hall current causes the electron response to get out of phase with the ion response; if the plasms radius (normalized by the collisionless skin depth) is less than the elongation (separatrix length-to-diameter ratio) then the mode is stabilized. Oddly, this scaling of the marginal stability boundary is the same as would arise from finite Larmor radius, an unrelated phenomena.

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Quantitative Analysis of Collisionless Tearing Modes in a Modified Harris Equilibrium

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We report on a quantitative analysis of the eigenmode equations for the collisionless tearing instability in a modified Harris equilibrium. This equilibrium, characterized by the magnetic field, $\mathbf{B} = B_{0y}\, 1_y + B_{0z} \tanh(x/L)\, 1_z$, has been invoked in a number of applications, notably to model field geometry in the magnetotail or magnetopause boundary layer. It is also theoretically interesting, since kinetic plasma responses can be accurately calculated near the singular layer, $\mathbf{k}\cdot\mathbf{B}(x_s) = 0$. In addition, these responses merge smoothly into the adiabatic responses appropriate far from $x = x_s$. This makes an accurate global analysis of the collisionless tearing instability in this equilibrium possible.

Analyses of tearing instabilities in the Harris equilibrium have usually invoked the "constant psi" approximation. Particularly notable is the recent work of Galeev, et. al., who analytically estimate the marginal stability of a modified Harris equilibrium to collisionless tearing and apply these results to a theory of the so-called flux transfer events observed in the magnetopause boundary layer [1]. We extend these results by numerically solving, as a global problem, the collisionless tearing eigenmode equations. Our initial results are in the differential formalism appropriate when the ion Larmor radius is small compared to the size of the region where the ion contribution to the parallel conductivity is significant. This calculation is intended to provide a foundation for two subsequent calculations, 1) a global integral equation based analysis of collisionless tearing in the modified Harris equilibrium, and 2) the consideration of other equilibria which more realistically model the magnetopause boundary layer.

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H–Mode Simulations of DIII–D Using Drift Wave Models

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Transport code simulations with drift wave models [1,2] have achieved some measure of success in describing the confinement time scaling of ohmically heated and L–mode beam heated tokamak discharges. The models associate dissipative trapped electron mode losses with neo-Alcator scaling, and the η_i mode losses with high density ohmic saturation and auxiliary power degradation. Using modified versions of our previous model [1] which incorporate changes in the onset of η_i mode turbulence for flat density gradients [3], the present work makes a comparative study of DIII–D L–mode and quasistationary H–mode discharges recently obtained with long pulse beam sources. In contrast to previous work, the η_i mode instability threshold for relatively flat density profiles, typically found in DIII–D H–modes, is characterized by a critical temperature gradient length rather than by a critical η_i [3]. This effect results from toroidal compressional stabilization. The goal of the H–mode simulations is to show that the unfavorable temperature scaling of the drift wave models can be ameliorated by other parametric dependences. In particular, the increased edge temperature of the H–mode reduces the bulk temperature gradient and may be sufficient to either stabilize or substantially reduce η_i mode transport in the bulk. The analysis of heat transport close to the temperature gradient threshold for the η_i mode presents challenging numerical problems not previously encountered [1] (ohmic and L–mode simulations were generally well above or below the η_i mode threshold).

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SHERWOOD THEORY MEETING 1988

A 3-D Code for Calculating Neutral Transport in Axisymmetric Plasmas *

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We have developed a 3-D code for calculating the neutral density arising from arbitrary unsymmetrical sources (such as the wall, limiter, gas puff, or any diagnostic neutral beams) in an axisymmetric background plasma. We use a scheme similar to the 1-D code ANTIC[1], with some extensions. A full local Maxwellian distribution is used instead of just a delta function at $\frac{3}{2}$KT. Iteration is used to solve the large number of simultaneous linear equations. Each iteration corresponds to a new generation of neutrals, and the process converges very rapidly. Wall recycling effects are included to all orders. We compare our results with ANTIC and Monte-Carlo calculations for a plasma with cylindrical symmetry. The code is completely vectorized, and runs very fast on VAX or CRAY. We plan to use it to calculate the halo of the diagnostic neutral beam now operating on TEXT.

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THE EFFECTS OF RADIAL MOMENTUM TRANSFER ON NEUTRAL BEAM DRIVEN CURRENTS IN TOKAMAKS

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A self-consistent theory is presented for the calculation of neutral beam (NB) driven currents in tokamaks, including the effects of radial transfer of momentum, which is responsible for the observed behavior of the ion toroidal velocity in NB experiments.

Starting from the steady-state continuity and momentum balance equations for a three species plasma (beam ions, plasma ions and electrons), an expression for the total current density in the toroidal direction, j_ϕ, is derived. It is found that j_ϕ is the sum of three terms:

$$j_\phi = j_{mom} + j_{bs} + j_{E_r}$$

where j_{mom} is a term proportional to the NB momentum input, j_{bs} a term proportional to the pressure gradients (bootstrap current), and j_{E_r} a term proportional to the radial electric field which, in this ordering, can be determined self-consistently.

This last term, the current density driven by the radial electric field, is a new effect and for typical tokamak parameters it is found to be proportional to $-E_r$. So, for strong co-injection, where the radial electric field E_r is mostly positive, j_{E_r} gives a negative contribution to the total current, while for nearly balanced injection, where the radial electric field is negative, j_{E_r} can give us a positive contribution.

The expression for the total current density, after taking the appropriate limit, reduces to that predicted by the standard theory which includes electron shielding and trapped electron effects, but not effects of radial momentum transfer.

Model problem calculations, with parameters characteristic of the recent high-confinement neutral beam heated plasmas in TFTR, predict a total current of 600 kA for 10 MW of nearly balanced NB injection, a result in agreement with the experimental observations, which show evidence of substantial non-Ohmic currents.

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Transport Theory of Impure Tokamak Plasma with Strong Rotation*

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Strong rotation ($V \sim v_{thi}$) has been suggested[1,2,3] to be able to alter the impurity transport in tokamak plasmas. Here, we present a transport theory of plasma with strong rotation and strong impurity ($\alpha \equiv \frac{n_I}{n_i} Z^2 \sim 1,\ Z^2 >> 1$), in which the poloidal density variations, poloidal flows, explicit viscosity tensors (with rotation and impurity), and the transport coefficients are calculated in detail in the Pfirsch-Schlüter regime, using a $\delta_p (\equiv \frac{\rho_{pi}}{l}$, where ρ_{pi} is the ion poloidal gyroradius and l is the scale length) expansion. It is shown that the zeroth order solution has a very strong impurity density variation ($\tilde{n}_I(\theta)_{max} > \bar{n}_I$) due to the super-sonic flow ($V \sim v_{thi} >> v_{thI}$); and hence, the approximation[1,3] $n_I = \bar{n}_I + \tilde{n}_I cos\theta$ is no longer appropriate. Actually, the form $n_I \propto\ exp(\frac{V_\phi^2}{v_{thI}^2})$ is also found not appropriate. To $0(\delta_p)$, we obtain the $0(\delta_p)$ poloidal flows (even without up-down asymmetric[4] B-field) and $0(\delta_p)$ up-down asymmetric poloidal density variations, driven by the $0(\delta_p)$ i-I friction due to the nonvanishing relative i-I diamagnetic flow. Furthermore, in the Pfirsch-Schlüter regime, to $0(\delta_p)$, we find a correction to Braginskii's viscosity tensor, due to rotation. Consequently, we find that plasma transport is importantly enhanced by the inclusion of impurities combined with strong rotation.

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Analytic Treatment for Mode Conversion in the ICRF Problem

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Abstract

One of the outstanding problems in ICRF heating of tokamaks is the mode-conversion process at the second harmonic gyro-resonance layer. The complexity of the problem is largely due to the presence of the several waves, i.e., incident and reflected magneto-sonic waves, ion-Bernstein wave, and particle modes (which are analogous to the ballistic modes in Landau damping). As a consequence, most of the work done on this problem has involved heavy numerical analysis. By considering the problem in wave phase space (x-k space), however, we can not only simplify it greatly, but also gain a better understanding of the physics of the process. In phase space, the mode-conversion occurs at two points, and by expanding the dispersion functions at those points, we can derive (using the WKB approximation) two sets of coupled linear first order equations:

$$[\omega \mp k_x c_{\mathrm{A}}]\, b_{\mp}(x,t) = \alpha_{\mp} \int dv_{\parallel}\, p(x,t;v_{\parallel})$$

$$[\omega - k_{\parallel} v_{\parallel} - 2\Omega_i(x)]\, p(x,t;v_{\parallel}) = \beta(v_{\parallel})\, b_{\mp}(x,t)$$

where $\omega \rightarrow i\partial/\partial t$, $k_x \rightarrow -i\partial/\partial x$, $b_{\mp}(x,t)$ is the magnetic perturbation of the magneto-sonic wave ($\mp$ denotes incident/reflected branches), and $p(x,t;v_{\parallel})$ is the $(v_x v_y)$ moment of the perturbed distribution function (it is thus termed *pressure-anisotropy wave*). $p(x,t;v_{\parallel})$ contains both the ion-Bernstein wave and the particle modes, which can be constructed by van Kampen analysis. Solving these equations, we can then obtain the coefficients of transmission, reflection, conversion and absorption analytically. These results are compared with those obtained by other authors using different methods. Our model also gives rise to a new phenomenon which we call the *linear ion cyclotron echo*.

The merit of the present approach is its power and simplicity. It can be extended without much difficulty to more realistic geometries, such as magnetic field with rotational transform and general density profile of plasmas in tokamaks.

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GLOBAL ICRF WAVE PROPAGATION IN EDGE PLASMA AND ANTENNA REGIONS USING THE 2-D FINITE DIFFERENCE CODE ORION*

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The two-dimensional (2-D) finite difference code ORION[1] has been modified to include a non-zero component of the ICRF electric field along $\vec{B}$ for both axisymmetric tokamak and helically symmetric stellarator geometries. Flux surfaces, conducting boundaries and antennas can be of arbitrary shape and the antenna current is divergence-free. Cartesian coordinates eliminate the singularity which occurs at the origin of cylindrical coordinate systems. Results for the high density central plasma region show good agreement with previous calculations[1-4] in the $E_{\|} = 0$ limit, and there is no evidence of numerical pollution due to the large parallel electron conductivity. With the inclusion of non-zero $E_{\|}$, it is possible to calculate the detailed structure of ICRF wave fields in just the edge-plasma region immediately surrounding the antenna. Artificial absorbers on the plasma side of the antenna simulate an outgoing-wave boundary condition. Phenomenon associated with a vacuum edge can now be studied, for example, coupling between antenna and plasma across vacuum regions (i.e., H-mode conditions).

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Transport Simulations of Ohmic and ECRH Experiments at TFTR, T-10 and TEXT*

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Recent theoretically-based models[1] for electron and ion confinement have been found in good agreement with ohmic[2] and neutral-beam-heated experiments on TFTR. Trapped-electron drift wave transport at low density was found to give rise to neoAlcator scaling and η_i driven ion transport was found consistent with the density saturation of the total energy confinement time for large plasmas. Studies of pellet-fuelled experiments on TFTR, ASDEX and ALCATOR-C were consistent with suppression of η_i-driven ion transport and improved confinement during the peaked profile phase following pellet injection.

Simulation tests of the microinstability-based models for anomalous confinement have been extended to experiments on T-10 and TEXT. Preliminary BALDUR simulations show that the TFTR calibration of the model gives reasonable agreement with measured temperature profiles and confinement times for ohmic, gas fuelled discharges on these machines, if we use a mass and charge scaling of χ_i and χ_e inferred from simulating hydrogen experiments on TEXT and helium experiments on TFTR.

Simulations of pellet fuelled experiments on TEXT show supression of the anomalous ion model transport consistent with the proposed η_i-mode identification of measured fluctuation spectra[3].

We find that the predicted electron temperatures with ECRH heating on T-10 are underestimated by the microinstability-based model.

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EVOLUTION OF HELICAL MAGNETOHYDRODYNAMIC TURBULENCE FROM A NEARLY FORCE-FREE INITIAL STATE[1]

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We investigate by means of numerical simulations the relaxation of an unconfined, helically turbulent, fully three-dimensional magnetofluid in which the effects of both resistivity and viscosity are considered. The initial conditions chosen for these simulations are similar to those which are thought to exist in turbulent, nearly force-free magnetofluids such as the solar corona or portions of an RFP "tangled discharge." In these simulations, the system evolves through a succession of force-free states. After a relatively quiescent period of Ohmic decay, a phase of accelerated magnetic energy dissipation occurs. Some magnetic energy is transformed into kinetic energy, and the magnitude of enstrophy created is a sizeable fraction of the mean square electric current. Concentrated vorticity structures are seen to play almost as important a role as electric current sheets both in determining the evolution and in the heating process. Coincident with this accelerated dynamic dissipation process, a reorganization of the magnetic field occurs, with transfer of energy to both shorter and longer wavelength modes than are initially present. Similar to the behavior observed in inviscid, confined Z pinch simulations[2], the ratio of the magnitude of the magnetic field and electric current density does not in general tend to assume a constant value in the force-free regions during the turbulent evolution of the magnetofluid. The applicability of our results to the coronal heating problem and to possible evolutionary aspects of the Rusbridge RFP tangled discharge model will be discussed.

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3D14

Analysis of Lower Hybrid RF Stabilization of Tearing Modes in the Tokamaks

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Recent considerable attention has been paid to stabilization of tearing modes on tokamaks via lower hybrid current drive. The stabilizing behavior of current drive on the magnetic island growth rate in the semi-collisional regime is analysed through the drift-kinetic equation. A 1D collisional operator is developed to model electron parallel conductivity. In this case, the total conductivity consists of two parts: one from bulk electrons in the absence of rf-power, and a second part caused by the superthermal electrons created by rf-waves. For typical PLT parameter. The resulting conductivity is 2-3 times greater than that of bulk electrons. Thus, the linear growth rate and quasilinear growth rate of the island in the Ruthurford regimes is decreased by a similar factor.

THREE-DIMENSIONAL PLASMA EQUILIBRIUM NEAR AN INTERNAL SEPARATRIX*

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We calculate explicitly the limiting behavior of a general three-dimensional MHD equilibrium solution as it approaches a separatrix. We make no assumptions about island width or beta. The calculation is based on the observation that the behavior of the MHD equilibrium near a separatrix is dominated by the x-point, so that the leading order behavior can be extracted quite generally. In the light of our solution, we examine some of the issues concerning existence of three-dimensional MHD equilibria. We also discuss some implications for the numerical computation of such equilibria.

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Stability of The "Peapod" Shaped Tokamak Against Low-n MHD Modes.

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We investigate the MHD–stability of a "peapod" shaped tokamak against low-n kink and pressure driven modes. The cross–section of a peapod shape has relatively sharp tips and some indentation on the inside of the tokamak, but unlike a crescent shape, it has a bulge toward the axis of symmetry at the midplane. This bulge increases the value of global plasma β without jeopardizing stability. The global β is defined as the ratio of the plasma energy to the total toroidal magnetic energy when the toroidal field magnets are assumed rectangular in shape. The motivation for the study is obtained from the results of tokamak shape optimization[1] with the sharp boundary model, using the same definition of the global β. We compute the stability of peapod equilibria with three elongations using the PEST code and compare the results with those obtained for a Dee–shaped and bean–shaped plasma. The high–β equilibria are produced with reasonable current profiles and small edge currents, while the edge safety factor is varied between $q_a = 3$ and $q_a = 8$.

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HOT-PARTICLE EFFECTS ON HIGH-n INSTABILITIES IN TOKAMAKS*

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Hot particles such as α-particles from fusion reactions and beam ions from neutral-beam-injection heating can have significant effects on high-n instabilities in tokamaks. These hot species can have strongly non-Maxwellian equilibrium distribution functions and can interact with the instabilities through resonances of several sorts; a kinetic analysis is therefore required to calculate the effects accurately. Results are presented from a comprehensive electromagnetic kinetic eigenfrequency eigenfunction code[1] for the trapped-electron drift mode and the MHD ballooning mode. This calculation includes magnetically trapped and untrapped particles for each species, with the corresponding bounce and transit frequency resonances (Landau damping), as well as the magnetic drift frequency resonances, and full finite Larmor radius effects. Relative quasilinear transport coefficients for particles and energy for each species are also calculated.

In high-temperature tokamaks capable of producing significant numbers of α-particles, such as CIT or TFTR, the effects of the hot α-particles and of the thermalized helium ash on these instabilities can be stabilizing, destabilizing, or negligible, depending on the parameters. For a CIT case, in particular, the α-particles can lower the critical β value for the MHD ballooning mode by a factor of three or more. In turn, the instabilities can cause significant anomalous transport of the α-particles and helium ash. None of the kinetic effects, except for the trapped-α time-average magnetic drift resonances, are included in the previous work[2] in this area, so the present work represents an extension.

Results will also be presented for TFTR in the so-called "super-shot" regime, where non-Maxwellian beam ions can constitute a significant fraction of the plasma. In particular, the beam species equilibrium distribution function can be strongly anisotropic in pitch angle, leading to significant additional terms in the mode equations[3].

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Computer Simulation of Transport Driven Current in Tokamaks

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The inductively pulsed mode of operation typical of tokamak experiments would be undesirable in a reactor; therefore, an efficient, non-inductive means of sustaining the toroidal current is needed. Recent experiments by Taylor et al[1] on the CCT tokamak at UCLA generate and maintain a steady state toroidal current in the presence of toroidal and vertical magnetic fields, but without any ohmic electric field. This current is observed in plasmas generated in a variety of ways, (filament discharge, ECRH, lower hybrid) and always flows in the direction required for equilibrium. This holds true even when the filament primary electron current is injected in the "anti-equilibrium" direction, or when the RF is injected without the sort of antenna structure or phasing which theoretically is required for RF current drive. The RF generated plasmas do not contain the fast electrons often associated with RF current drive; therefore, the current is carried by the bulk of the electron distribution, not an energetic "tail". The toroidal current apparently results from a dynamo action due to a net plasma flow in the major radial direction. We have constructed a 2½ dimensional electromagnetic particle code which can model many of the features of a tokamak. Like the CCT experiment, the model shows that a Maxwellian plasma in d.c. toroidal and vertical fields spontaneously generates a toroidal current. In the simulation, that current can be large enough to close the poloidal magnetic surfaces. This transport driven current may be related to the bootstrap current[2,3,4], but the underlying transport which drives the current may not be neoclassical. If the position of the plasma source can be adequately controlled via pellet injection, and there is a steady state source of heat (the alpha particles in a reactor) then such transport driven current might supply a large fraction of the required toroidal current. The results of numerical simulations will be presented and compared with various theoretical predictions.

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Interaction of A Neutral Beam and An Ambient Plasma

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We have developed 2 and 3-d computer models with kinetic ions and massless fluid electrons. Those codes have been rigorously tested by the comparison of their predicted wave modes with those of the linear analytic theory; the agreement is good. We generalized the code to include interaction of a background plasma with a gradually ionizing gas which has a relative drift speed with respect to the background plasma. The important problem to which we have apllied this has been the neutral beam heating of a fusion plasma. In that regard we have used the model to study the microinstabilities which arise from a velocity ring. The growth rates of the various modes propagating at right angles to an external magnetic field have been measured and thus the most unstable modes have been found. The nonlinear mode saturation was observed which might have well been due to ion trapping. More interesting was the generation of the peaks of the power spectra at the various ion cycltron harmonics for all the wave modes. This could well explain recent experimental results from the JET facility (Phys. Rev. Letters vol. 60 p33 Jan 1988) in which strong emission lines close to ion cycltron frequencies were observed upon injection of neutral beams. Thus it could well establish some theoretical understanding of the experimentally observed phenomenon.

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RF TOKAMAK PLASMA CONFINEMENT DUE TO BRILLOUIN SCATTERING OFF TRAPPED PARTICLE MODES IN LOWER HYBRID FREQUENCY RANGE *

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We study Brillouin scattering of rf field in lower-hybrid frequency range (LHFR) off dissipative trapped particle modes (TPM) ($\omega < \Omega_i$, Ω_i local electron cyclotron frequency) in tokamak environment. In our calculation nonlocality of TPM is taken into account and driver pump is treated as fast or slow wave as separate roots of fourth order propagation equation. We show that TPM stabilization is a consequence of resonant nonlinear coupling[1-3] to lower hybrid waves (LHW). Stabilization of TPM leads to enhancement of LHW turbulence level and influences particle and energy confinement time. We evaluate capabilities and constraints of this interaction for dynamical rf confinement of tokamak plasma in LHFR.

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IDEAL STABILITY OF AXISYMMETRIC TOROIDAL PLASMAS WITH SHEARED EQUILIBRIUM FLOWS

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Recently, it has been observed in TFTR that neutral beam injection gives rise to a bulk rotation of the plasma of the order of the sound speed. The experimental observations have been interpreted by a WKB theory of $n \rightarrow \infty$ ballooning modes, and a new instability has been indentified. It has emerged that the standard WKB formalism breaks down for $n \rightarrow \infty$ modes when the equilibrium flow is purely toroidal and sheared. In this paper, we address this situation by deriving a general energy principle which gives sufficient conditions for stability for all ideal modes, including kink and ballooning. We then develop a finite n WKB theory by introducing the high β tokamak ordering. We show that under certain conditions on the shear in purely toroidal flow, it is possible to restore the ballooning structure for finite-n modes. We give sufficient conditions for stabilility.

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Parametric Quasi-Mode Decay at Lower Hybrid Geometric Foci**

Inho Park and Jean-Marie Wersinger, Physics Department, Auburn Univ., AL 36849 – Numerical studies with LHRAYS have shown the existence of true 3D foci in circular cross section tokamaks. This can be understood if we consider the plasma acting much like a lens. The foci of interest in tokamaks are line foci directed along the toroidal direction, and such that the pump extent in the poloidal cross section is reduced as the focus is approached. The existence and the location of foci depend both on the initial conditions of the rays and on the properties of the medium. By varying parameters such as pump frequency ω_0, central plasma density n_0 and parallel refractive index $N_{0||}$, we found that these foci were structurally robust.

In order to study quasi-mode parametric decay at geometric foci, we set up an analytic pump model* assuming the rays to be straight. Since quasi-mode decay is a convective instability, the time of flight τ of daughter waves is limited by their convection out of the pump extent. We have found that there are three regions which show different convective properties. In Region 1 which is near the focus, τ is governed by the poloidal pump extent. In Region 3 which is far from the focus, it is governed by the toroidal pump extent. Region 2 between them is transition region. The pump wave energy density W_0, and thus the quasi-mode growth rate γ_g increases as the focus is approached. Using our model, qualitative aspects of daughter wave amplification have been studied. Daughter wave amplification increases drastically in Region 3 as the focus is approached. But in Region 2 the rate of increase of daughter wave amplification is strongly reduced. Furthermore daughter wave amplification is constant in Region 1. Therefore, if the depletion of the pump wave is not severe at the boundary of Region 1, the quasi-mode decay does not prevent the wave energy from building up at the focus, and other nonlinear effects like ponderomotive effects may be expected. Thus we are interested in how much the daughter wave is amplified and how much the pump wave is depleted. To do this, we have run the ray tracing code LHRAYS with focusing on. Using the numerical data of this code for the pump wave energy density, we compute daughter wave amplification in the three different regions. Results of the maximum amplification of the daughter wave for some tokamaks are given. The final goal of this work is to compute the depletion length and to address the possibility for nonlinear ponderomotive effects to occur.

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CROSS-FIELD SHEATH IN A MAGNETIZED PLASMA*

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A self-consistent model of the equilibrium electrostatic sheath formed between a magnetized plasma, $\underline{B} = \underline{B}_0$, and an absorbing wall, with unit normal $\underline{n}$, is presented. The external magnetic field is nearly parallel to the wall, i.e. $\cos\theta = \underline{n} \cdot \underline{B}_0 / |B_0| \ll 1$. The ions, which are treated kinetically, have an unperturbed distribution function which is a Maxwellian, modified by the prescription that ions which have hit the wall are absent. For the electrons, a warm fluid model, including electron-neutral collisions of frequency ν, is used. The transport of particles due to turbulence is modeled to lowest order by allowing a small d.c. electric field parallel to the wall. For $\theta = 0$, analytic solutions for the sheath fields are obtained using a boundary layer approach, with approximate expressions for the ion density profile. The wall potential is positive with respect to the plasma and the structure of the sheath is divided into two regions: a highly nonneutral region adjacent to the wall, with a thickness of the order of the Debye length, and a quasineutral region, whose width is of the order of the ion cyclotron radius. Such sheath solutions exist for specified values of the potential drop and particle flux over a large range. The transition from this magnetized sheath (parallel magnetic field, $\theta = 0$) to the unmagnetized sheath (oblique magnetic field, θ small but non zero) is presently being analyzed.

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IMPURITY TRANSPORT IN A ROTATING TOKAMAK PLASMA*

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Simulation[1] of impurity ion orbits in a toroidally rotating tokamaks, based on the guiding-center equations of motions in the frame that rotates with the plasma, are carried out with realistic experimental parameters. Pitch-angle scattering of the impurity ions and the thermal equilibration between the core ions and impurity ions are included in the simulations. It is found that in a rotating plasma the impurity ions can drift away from the magnetic surfaces significantly faster with a higher bounce frequency and a larger banana width, resulting in a diffusion coefficient much larger than that for a stationary plasma. The computed impurity diffusion coefficient can qualitatively fit the experimental data[2] on the temporal evolution of impurity line radiation in the energetic ion mode plasma in TFTR.

Particle orbits near the surface of a rotating tokamak are also analyzed. Since the Coriolis force depends on $\vec{v}_\parallel$, the banana orbit is asymmetric with respect to the magnetic flux surface, and the orbit excursion is larger on the outside with co-injecting beams and vice versa. Freshly ionized impurity ions, essentially stationary in the laboratory frame, are counter-rotating in the plasma frame and their first banana orbits move outward in minor radius. This explains the experimental observations[1,3], that more impurities can penetrate into a plasma rotating with counter-beam injection.

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MODE CONVERSION AND ABSORPTION OF LOWER HYBRID WAVES IN INHOMOGENEOUS MAGNETIC FIELDS*

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When a cold lower hybrid wave propagates in an inhomogeneous plasma, it undergoes a total mode conversion to the warm wave which is then coupled with the ion Bernstein wave around ion cyclotron harmonic frequencies. Both types of linear mode conversion problems can be described by fourth order differential equations if the two processes are separated from each other. The governing equation for the mode coupling at high harmonics is shown to be identical in form to that of the second harmonic problem.

The combination of the two types of mode conversion when the lower hybrid turning point is in the vicinity of a cyclotron harmonic requires a sixth order equation with a quadratic coefficient, for which the usual technique utilizing the Laplace transform has no advantage since the transformed equation is second order and the general solution is not available. Some numerical methods are applied without success. Another type of sixth order equation, which has only linear coefficients and represents the three wave problem marginally, is solved analytically without including the absorption term. Applying the results of this analysis, it is shown that the direct mode coupling to the ion Bernstein wave from the incident lower hybrid wave takes place effectively only when the lower hybrid turning point is very close to the harmonic resonance such that the distance between their respective turning points is similar in magnitude to the common wave length of the coupling.

Finally, the damping and the absorption of the wave are compared for the unmagnetized dispersion relation, the full magnetized dispersion relation, and the mode conversion analysis as the wave propagates in a magnetically confined plasma with slab geometry. The unmagnetized ion model approximates the overall damping rate, averaged over space in some sense, compared with the ion cyclotron model. However, any model without the mode conversion analysis, whether magnetized or not, always overestimates the absorption of the wave energy by ions, and the difference is very often significant. The mode conversion to ion Bernstein waves, from the warm wave or on rare occasion from the cold wave, is a possible mechanism explaining the poor ion heating observed in lower hybrid ion heating experiments.

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Generating Functions and Toroidal Magnetic Fields

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It is well known that the magnetic field line equations have a Hamiltonian structure with the toroidal angle playing the role of the time-like variable[1]. This is due to the divergence-free nature of the magnetic field. Because $\mathbf{B}(\mathbf{x})$ is divergence-free it can always be written in the following form[2]:

$$\mathbf{B}(\mathbf{x}) = \nabla\psi \times \nabla\theta + \nabla\varphi \times \nabla\chi$$

where ψ, θ, φ and χ are well defined functions of position. We take ψ as the toroidal flux, θ as the poloidal angle and φ as the toroidal angle. If we follow a magnetic field line using the toroidal angle, φ, as a curve parameter, then ψ and θ change according to:

$$\frac{d\theta}{d\varphi} = \frac{\partial\chi}{\partial\psi} \qquad\qquad \frac{d\psi}{d\varphi} = -\frac{\partial\chi}{\partial\theta}$$

Thus, the field line equations are Hamiltonian, with χ playing the role of the Hamiltonian and φ the time. This implies that the map which takes a field line once around the torus is a canonical transformation and that a generating function exists which generates this transformation for an arbitrary number of passes. The most important advantages of this approach to the study of toroidal field structure are a) the map is effectively an implicit integration scheme which allows arbitrarily large time steps, b) once the generating function is known no more magnetic field evaluations are required, c) the divergence-free property of the magnetic field is <u>automatically</u> guaranteed and d) the generating function contains all of the topological information about the magnetic field. The properties of the generating function for multiple toroidal transits will be discussed. The scaling behavior of the generating function for N passes as N becomes large is of particular interest.

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ALPHA PARTICLE INDUCED FISHBONE OSCILLATIONS*

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ABSTRACT

The successful modelling[1] of $m^{o}=1$ fishbone oscillations in beam-injected plasmas naturally leads to considering the possible excitation of such oscillations by α-particles in fusion burning plasmas. The main ingredients for this are: (1) the ideal MHD instability parameter must fall in the range $0 < \lambda_H < (1/2)\ (\omega_{di}/\omega_A)$ where ω_{di}, ω_A are the core-ion diamagnetic and Alfven frequencies, (2) a viscous-like mode-particle resonant interaction must occur, $\omega \simeq \omega_D^{(o)}$ (the bounce averaged precession drift frequency of trapped energetic particles). From our analysis, three results emerge: (1) for $\omega \simeq \omega_{di}$, the ideal MHD parameter is modified $\lambda_H \rightarrow \lambda_H + \lambda_{KR}$ where $\lambda_{KR}(\omega \simeq \omega_{di}) < 0$. This causes the fishbone mode to become macroscopically stable as $\beta_{p\alpha}$ increases past a critical finite value. (2) the decrease of $\lambda_H + \lambda_{KR} < \lambda_H$ in the presence of α-particles can bring the better known $m^{o}=1$ mode (so-called ideal internal kink) closer to stability. (3) A higher frequency oscillation, whose instability is supported entirely by trapped energetic particles, can be excited (if $\beta_{p\alpha} \gtrsim 1$) with $\lambda_{KR}\ (\omega \simeq \omega_D^M) > 0$ where ω_D^M is a measure of the precession frequency of alphas with 3.5 MeV energy.

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MAGNETIC HELICITY INJECTION FOR CONFIGURATIONS WITH FIELD ERRORS*

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Recent RFP experiments have shown that there is a dramatic decrease in the loop voltage in RFP's when field errors at the plasma edge are minimized. Several models involving magnetic helicity have been invoked to explain these effects.[1] Here, the relative magnetic helicity[2] is computed for several examples of configurations representing magnetic fusion experiments, specifically RFP's, with field errors. The perturbations producing these errors can arise from imbalance of the vertical field, leakage of ohmic transformer flux, or toroidal field ripple. In the examples given, the relative helicity is the difference between two terms, which we call, respectively, the plasma linkage and the vacuum linkage. The latter quantity, which is zero for the simplified configurations previously studied,[2] represents the linkage between vacuum fluxes occuring within the region of interest. The plasma linkage, on the other hand, is the part of the relative helicity directly related to the instantaneous state of the plasma. Surprisingly, the helicity injection rate is not simply a sum of the usual inductive and electrostatic helicity injection terms. Based upon these expressions, we present several interpretations of helicity injection involving linkage of injected fluxes, and line tying to equivalent moving conducting walls.

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NEOCLASSICAL QUASILINEAR TRANSPORT THEORY OF FLUCTUATIONS AND ITS APPLICATIONS*

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The neoclassical transport theory of fluctuations with frequencies less than the gyrofrequency in toroidal plasmas is developed in order to calculate particle and heat fluxes, the bootstrap current, the Ware pinch flux, and the modification to plasma conductivity. It is found that the particle and heat fluxes are proportional to $\sum_{m,n} m^2(e\tilde{\Phi}_{mn}/T_e)^2$, the bootstrap current and Ware pinch flux are proportional to $\sum_{m,n} m\left[(m-nq)/|m-nq|\right](e\tilde{\Phi}_{mn}/T_e)^2$, and the modification to plasma conductivity is proportional to $\sum_{m,n} |m-nq|(e\tilde{\Phi}_{mn}/T_e)^2$, where $m\,(n)$ is the poloidal (toroidal) mode number for the (m,n) mode, $\tilde{\Phi}_{mn}$ is its mode amplitude, e is the electric charge, T_e is the electron temperature, and q is the safety factor. Thus, the sensitivities of various transport fluxes to plasma fluctuations are different: the most sensitive ones are the particle and heat fluxes, the less sensitive ones are the bootstrap current and the Ware pinch flux, and the least sensitive one is the modification to the plasma conductivity. It is demonstrated explicitly that the matrix consisting of these transport coefficients satisfies Onsager symmetry. Furthermore, it is shown that electron and ion transport are coupled through plasma flows or the radial electric field. The theory is employed to discuss some qualitative transport properties in toroidal plasma experiments. It is found that the fluctuation-induced transport fluxes are reduced if the radial electric field is more negative. This result is employed to explain the confinement degradation (density clamping) in tokamaks with co-injected neutral beams and confinement improvement in counter-injected tokamaks. A model for the L-H transition is developed from the conjecture that the transition is caused by a sudden change in the radial electric field. The change of the radial electric field is triggered by enhanced ion orbit losses when $\nu_{*i} < 1$. The power threshold scaling $P_{\rm th} \propto N^3 q\epsilon^{3.3} R^{4.3}/I_p^2 M_i$ for the H-mode is obtained from the onset condition $\nu_{*i} = 1$, with N the plasma density, I_p the plasma current, and M_i the ion mass. There are also an inward component of particle flux and its Onsager conjugate: an inward component of heat flux. Because of the existence of these inward components of particle and heat fluxes, the particle diffusivity and heat conductivity deduced from density pulse and heat pulse experiments are larger than those inferred from power balance calculations. The theory is extended to include nonlinear particle dynamics and to apply in the collisional regime.

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NONLINEAR GYROKINETIC MAXWELL-VLASOV EQUATIONS USING MAGNETIC COORDINATES*

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An axisymmetric tokamak equilibrium configuration can be represented by $B = g(\psi_p)\nabla\xi + I(\psi_p)\nabla\theta + \delta(\psi_p,\theta)\nabla\psi_p$ where (ψ_p,θ,ξ) are magnetic coordinates.[1,2] A gyrokinetic formalism using these magnetic coordinates is used to derive self-consistent nonlinear Maxwell-Vlasov equations that are suitable for the study of finite-β microturbulence in tokamak plasmas.

The use of magnetic coordinates is an important feature of this work as it introduces the toroidal geometry naturally into our gyrokinetic formalism. The gyrokinetic formalism itself is obtained through the use of the action-variational Lie perturbation method and preserves the Hamiltonian structure of the original Maxwell-Vlasov system. Our derivation involves only the use of the parallel component of the perturbed vector potential; the fully electromagnetic problem is discussed with the help of the gyroaveraged particle-Hamiltonian. The magnetic drifts are given in terms of the Poisson brackets, i.e., $\dot{\psi}^i = \{\psi^i, H\}$, and contain terms up to second order in perturbed potentials, thus generalizing the Hamiltonian guiding-center theory of White et al.[2]

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SECOND HARMONIC ECH PLASMA BREAKDOWN: A COMPARISON OF THEORY WITH INITIAL EXPERIMENTS IN ATF*

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According to the linear theory of 2nd harmonic electron cyclotron heating the power absorption is proportional to $n_e T_e$.[1] Therefore, to explain the breakdown of a cold gas and subsequent build up of plasma density a nonlinear mechanism must be invoked. Such a nonlinear interaction has previously been proposed[2] in which deeply trapped electrons undergo a coherent interaction with the right circularly polarized component of the wave field, E_-. The effect of the interaction is to produce a periodic oscillation of particle energy with frequency, $\nu_{\rm rf} \approx 500 |E_-| \sec^{-1}$ and an energy variation $\Delta\epsilon \approx |E_-|/3f$ where $|E_-|$ is in V/m and f is the wave frequency in GHz. However, in the presence of plasma or neutral gas, collisional decorrelation destroys this nonlinear mechanism when $\nu_{\rm rf} \leq (\nu_{ec} + \nu_{en})$, where ν_{ec} and ν_{en} are the electron Coulomb and neutral collision frequencies respectively. Thus, as the plasma density increases, linear cyclotron damping must take over if the discharge is to be maintained.

Experimentally it is observed that in many discharges the initial breakdown does occur with fill pressures which are roughly consistent with the nonlinear theory. Subsequently n_e and T_e rise although T_e reaches a maximum then steadily drops because of impurity radiation or excessive gas from the walls. At the time that T_e reaches zero (or unmeasurably small values) the rising density abruptly begins to drop and impurity line radiation rapidly decreases. This phenomenon, which as previously been observed on Heliotron-E, is known as 'dead plasma syndrome.' Also, it is observed that the duration of the discharge before the onset of 'dead plasma syndrome' is steadily improved by various cleaning techniques. This syndrome is modeled as a combination of impurity radiative cooling, which decouples the plasma from linear heating, and increased electron collisionality, which shuts off the energetic particle source provided by the nonlinear interaction. A comparison between these predictions and the most recent data from ATF will be presented.

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MAGNETIC TEARING OF PLASMA DISCHARGES DUE TO NONUNIFORM RESISTIVITY*

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Under some circumstances, the resistivity in a plasma discharge may be rendered nonuniform within a magnetic surface. In tokamaks, for example, this may happen in the presence of "marfes" or during pellet injection; in solar coronal loops, the resistivity near the footpoints may be highly inhomogeneous as a result of the subphotospheric convection. The rearrangement of current in a plasma discharge in response to resistivity nonuniformities within a magnetic surface is studied. It is shown that macroscopic magnetic islands develop about those surfaces where the nonuniformity is aligned with the magnetic field. If the nonuniformity and the field are nowhere aligned, there is no current rearrangement; instead, relatively large plasma flows are set up. In the case where the nonuniformity and the field are aligned, we show that magnetic islands grow as $w(t) \sim (\eta t)^{1/2}$, where w is the island width and η is the resistivity. These islands saturate at the critical width, $|\Delta'(k)w| \lessgtr 1$, if $\Delta' < 0$, where $\Delta'(k)$ is the usual linear tearing mode stability parameter. If $\Delta' > 0$, the growth continues past the critical width but reverts to the Rutherford rate, $w(t) \sim \eta\Delta' t$. In the case of no alignment, the plasma flows set up are of the order of η/ (macroscopic scale size) and therefore larger than Pfirsch-Schluter diffusion. Implications for marfes, pellet injection, and solar loop filamentation will be studied.

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SHERWOOD THEORY MEETING 1988

Dissipative Trapped Particle Modes in Tandem Mirrors*

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A variational dispersion relation covering collisional trapped particle modes in tandem mirrors and flute modes is derived.[1] By taking into account equilibrium rotational effect, electron and ion gradients, axial ambipolar potential, energetic particle, ion Landau damping and collisional effects the theory is used to investigate the realistic experimental observation (TMX-U) in which the low-frequency mode ($f \approx 2 - 7KH_z$) has been a major concern for the instability modes. A previous study[2] has assumed that the instability can be flute-like modes, where the equilibrium rotation drift ($E \times B$) is considered as the primary driving force. The theory predicts the oscillation frequency and instability threshold which are to some degree consistent with the experimental data. In this work, the derived dispersion relation includes the flute modes as sub-branches. The more general dispersion relation is used to examine the possibility to explain the observed modes as collisional trapped particle modes. Analytic and numerical studies show that the trapped particle modes still have strong influence from the $E \times B$ rotation drift and the mode frequency is close to what the flute mode theory predicts. However, the trapped particle mode theory does not suggest an explicit threshold for the instability.

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The Effect of Compressibility on Linear and Nonlinear Resistive MHD Toroidal Calculations*

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The inclusion of compressibility effects on resistive MHD numerical calculations makes the problem much more difficult due to the new time scale that must be followed. This new time scale is that of the fast or compressible Alfvén wave. In the computer code FAR[1], this time scale is accommodated differently depending on whether a linear or a nonlinear calculation is being done. For the linear case the code is fully implicit and a large time step can be used which effectively excludes the fast waves, or a small time step can be used which follows the fast motion. When applied to the resistive $m = 1$ kink instability, both time steps lead to identical linear eigenfunctions as long as the time step is not so large as to select the second most unstable mode. For the nonlinear case the numerical problem requires a much shorter time step since the nonlinear terms are included explicitly. In order to use a time step that is long enough to minimize machine time requirements, an additional term is added to the compressible equation of motion. This term damps the fast wave motion but does not alter the linear eigenfunction. This is analogous to, but not the same as, the semi-implicit scheme.[2] Both linear and nonlinear results will be shown together with comparisons with the cylindrical code CYL.[3] Compressible and incompressible calculations will be compared.

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AN IMPROVED METHOD FOR CALCULATING BOOZER COORDINATES IN STELLARATORS*

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The use of Boozer coordinates[1] provides better physical insight into particle orbit trajectories and simplifies their calculation. Calculation of this set of flux coordinates[2] is performed by integrating along a field line, storing $B \equiv |\mathbf{B}|$ and $\chi = \int B d\ell$, and taking the FFT of $B(\chi)$.

For a field line which starts at a symmetry plane and at $Z = 0$, the peaks of the spectrum occur at intervals proportional to $n - \iota m$, where n is the toroidal mode number, m the poloidal mode number, and ι is the rotational transform. The method may fail in two ways: 1) if $\iota = n/m$, the surfaces is rational, 2) if ι is large so that the harmonics associated with each n value overlap. In each case it is difficult to determine the correct n, m values to assign to the peak, and peaks with differing n, m values may lie on top of each other making it hard to determine the amplitudes of the overlapping peaks.

For example, in the high ι Heliotron-E device, the spectra overlap on the outer flux surfaces, causing up to 50% errors in some harmonics, and 10% errors in the reconstruction of B.

If we represent B in terms of its toroidal and poloidal harmonics:

$$B = \Sigma B_{nm} \cos(n\phi - m\theta) \quad ,$$

we can separate the harmonic spectra of the B_{nm} by following two field lines, one starting at each of the two symmetry planes (on the same flux surface). The resulting spectra are related by

$$B_{nm}^{(1)} = (-1)^n B_{nm}^{(2)} \quad .$$

By adding and subtracting the two spectra, the harmonics corresponding to odd n (sum) or even n (difference) can be eliminated.

Examples illustrating this technique will be discussed.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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Wall Reflection Model for the RAYS Code*

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In an RF heating experiment, ECH microwave power that is not absorbed on the first pass through the plasma is partially lost to the metallic walls and partially scattered back to the plasma. If the first pass absorption is not significant, then the fraction of power which ultimately ends up in the plasma is a complicated interaction of wall characteristics (resistivity of the wall, geometry of the wall, etc.), plasma parameters, and magnetic geometry. In the past, others have treated this problem by adopting a model for the wall and tracing rays through multiple reflections. We take a different approach in which we assume that the power not absorbed on the first pass is quickly isotropized throughout the vacuum chamber. We treat the fate of this scattered power by doing a ray tracing calculation approximating rays homogeneously distributed and propogating isotropically. By folding in the first pass ray tracing and the wall loss which occurs at each reflection, we arrive at an approximation to the total power deposited in the plasma after an infinite number of reflections. Building on earlier work in which this model was first presented[1], we display second harmonic ECH calculations for the ATF torsatron. Results are given as the magnetic field level is varied causing the central "X-point" in the Mod-B contours to sweep through resonance. When the per-pass absorption is weak, the effect of multiple wall reflections causes the power deposition to be quite different from that of the first pass result alone. The scaling with temperature and density variation is also given to compare with the preliminary ATF data.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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Heating and Fuelling Effects in Simulations of a Density Limit in Radiation-Dominated Tokamak Discharges*

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Using tokamak transport simulation methods described previously[1], the authors consider the impact of auxiliary heating and impurity concentration on the density limit set by radiation. We will separately investigate particle transport and fuelling effects. Study of the latter topic is motivated by the fact that the shape of the density profile is found to be important in determining the maximum average density that can be sustained against radiation. Furthermore, Greenwald et al. have proposed[2] that the experimentally-observed density limit at a given current is caused by a rapid deterioration of central particle confinement with increasing density. We will examine the responses predicted by various particle transport models to fuelling transients in radiation-dominated tokamak simulations and determine their impact on the density limit. The fuelling transients will be provided by pellet injection or gas puffing.

*This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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