

Sherwood '87

1987 Sherwood Theory Conference

April 6-8, 1987 ♦ San Diego, CA

ANNUAL CONTROLLED FUSION THEORY MEETING

1987
**Sherwood Controlled Fusion Theory
Conference**

April 6—8, 1987
Holiday Inn—Embarcadero
San Diego, California

Hosted by
Science Applications International Corporation
San Diego, California

**Executive
Committee**

D.C. Barnes,
Chairman
J. Van Dam,
Secy./Treasurer
C. Birdsall
J. Cary
B. Cohen
J. Drake
J. Freidberg
L. Hedrick
F. Hinton
D. Monticello
R. Moses
S. Prager
W. Sadowski

**Program
Committee**

J. Freidberg,
Chairman
J. Cary,
Vice Chairman
V. Chan
R. Cohen
D. Dobrott
R.D. Hazeltine
J. Holmes
S. Jardin
R.A. Nebel

**Local Arrangements
Committee**

D. Dobrott,
Chairman
B. Vidler,
Conference Coordinator
D.C. Barnes
F. Hinton
B. Sarfaty
D. Schnack
M. Thompson

GENERAL INFORMATION

- * 217 papers were submitted, of which 13 were selected for oral presentation.
- * The Review papers will be presented in the Pacific Ballroom, Monday and Tuesday mornings beginning at 8:30 am.
- * All oral papers will be presented in the Pacific Ballroom, Monday and Tuesday mornings beginning at 9:30 am. Each talk will be 25 minutes in length plus 5 minutes for discussion.
- * A special session honoring Marshall Rosenbluth's 60th birthday will be held on Tuesday afternoon beginning at 2:00 pm in the Pacific Ballroom.
- * Poster sessions will be held in the Pacific Ballroom-D Section, Monday afternoon, Tuesday evening, and Wednesday morning.
- * A Reception will be held on Sunday evening, 8:00-10:00 pm, poolside.
- * Refreshments will be served consisting of coffee and tea during the morning sessions; beer and soft drinks during the afternoon and evening sessions.
- * Information can be obtained from the Conference Registration Desk regarding local sights, restaurants, and transportation.
- * Requests for special meetings should be made with Bonnie Vidler at the Conference Registration Desk.

1987 SHERWOOD THEORY CONFERENCE SCHEDULE
HOLIDAY INN-EMBARCADERO
APRIL 6-8, 1987

Registration

April 5, 1987 - 6:00-10:00 pm
April 6-7, 1987 - 8:00 am-5:00 pm
April 8, 1987 - 8:00 am-1:00 pm
Registration Foyer

Reception

April 5, 1987 - 8:00-10:00 pm
Poolside

Oral and Poster Session Schedule
Reviews and Orals - Pacific Ballroom
Posters - Pacific Ballroom-D Section

Monday, April 6, 1987

Welcome - 8:20 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 - 4:10-6:10 pm (Poster Session)

Tuesday, April 7, 1987

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 - 9:10-11:00 pm (Poster Session)

Wednesday, April 8, 1987

3A - 9:00-11:00 am (Poster Session)
3B - 11:10 am-1:10 pm (Poster Session)

Coffee and Tea - 10:00 am, Monday through Wednesday
Beer and Soft Drinks - 3:00 pm, Monday; 8:00 pm, Tuesday

1987 SHERWOOD THEORY CONFERENCE
ANNUAL CONTROLLED FUSION THEORY CONFERENCE

Holiday Inn-Embarcadero
San Diego, California
April 6 - 8, 1987

MONDAY MORNING 8:30 - 12:40pm

WELCOME 8:20

1A REVIEW SESSION

8:30am Pacific Ballroom
Presiding: Donald Dobrott

- 1A1. Physics Basis for the Compact Ignition Tokamak. R. R. Parker.

1B ORAL SESSION - Tokamaks

9:30am Pacific Ballroom
Presiding: Steve Jardin

- 1B1. Fully Toroidal MHD Nonlinear Studies of the $m=1$ Fast Sawtooth Crash. L. A. Charlton, B. A. Carreras, J. A. Holmes, V. E. Lynch, R. J. Hastie, and T. C. Hender.
1B2. Ideal Internal Kink Modes and Rapid Sawtooth Crashes. A. Y. Aydemir.
1B3. Tearing Modes in Toroidal Geometry. J. W. Connor, S. C. Cowley, R. J. Hastie, T. C. Hender, A. Hood, and T. J. Martin.
1B4. Modelling of Temperature Profiles and Transport Scaling in Auxiliary Heated Tokamaks. J. D. Callen, J. P. Christiansen, J. G. Cordey, P. R. Thomas, and K. Thomsen.
1B5. 3D Computational Study of Electron Cyclotron Heating and Current Drive. R. W. Harvey, M. G. McCoy, and G. D. Kerbel.
1B6. Radiative Condensation Instabilities in Tokamak Edge Plasmas. J. F. Drake and P. N. Guzdar.

LUNCH 12:30 - 2:00

MONDAY AFTERNOON 2:00 - 6:10pm

1C POSTER SESSION

2:00 - 4:00pm Pacific Ballroom

- 1C1. Hot Electron Stabilization of Ballooning Modes in Tokamaks. R. L. Miller.
1C2. Dynamic Global Access to Second Stability in Auxiliary Heated Tokamaks. G. Y. Fu, J. W. Van Dam, and M. N. Rosenbluth.
1C3. Equilibrium Alfvén Fluctuations due to Discrete Particle Effects. Y. Z. Agim and S. C. Prager.
1C4. Chaotic Field Line Resistivity and Viscosity and Their Effect on the Tearing Mode. J. M. Finn.
1C5. Synchrotron Radiation in Plasmas. M. Heindler and A. Nassiri.

- 1C6. Lower Hybrid Wave Propagation in a Tokamak. D. C. Stevens and H. Weitzner.
- 1C7. Compressibility and Temperature Effects in Toroidal MHD. J. A. Holmes, B. A. Carreras, L. A. Charlton, V. E. Lynch, R. J. Hastie, and T. C. Hender.
- 1C8. Alfvén Wave Heating with a Single Impurity Species. W. Q. Li, D. W. Ross, and S. M. Mahajan.
- 1C9. Evaluation of the Slowing Down Tail Enhanced Neoclassical Alpha Particle Energy Flux. P. J. Catto.
- 1C10. Energy Cascades in Almost Two-Dimensional Turbulence. J. M. Albert, P. L. Similon, and R. N. Sudan.
- 1C11. Ponderomotive Stabilization of High-N Ballooning Modes in Tokamaks. P. L. Similon.
- 1C12. Axisymmetric Ideal MHD Equilibria with Flow. Y. Baransky and C. K. Chu.
- 1C13. Application of the PIES Code to CIT Equilibria. J. L. Johnson, A. Reiman, J. Manickam, and A. H. Boozer.
- 1C14. Equilibrium and Stability of the Davis Diverted Tokamaks. D. E. Shumaker, D. Q. Hwang, and S. C. Jardin.
- 1C15. Anode Plasma Expansion in Magnetically Insulated Diodes. C. Litwin and Y. Maron.
- 1C16. Coupling of Ion Bernstein Wave from a Loop Antenna. S. C. Chiu.
- 1C17. Three Dimensional Studies of Lower Hybrid Wave Launching. A. Drobot, W. Grossmann, and L. Seftor.
- 1C18. New Developments in the Theory of Ion Temperature Gradient Driven Turbulence. P. W. Terry and P. H. Diamond.
- 1C19. Experiences Parallelizing a 3-D MHD Code. A. A. Mirin.
- 1C20. Simulation of Poloidal Current Heating in a High Beta Tokamak. X-L. Li, C. K. Chu, and T. C. Marshall.
- 1C21. Transport Induced by a Crossed-Field Sheath. K. Theilhaber.
- 1C22. Nonthermal Ion Cyclotron Emission from Optically Thick Plasmas. R. D. Sydora, J. M. Dawson, and V. K. Decyk.
- 1C23. Analysis of Lower Hybrid RF Stabilization of Sawteeth in the Alcator C Tokamak. P. Bonoli and M. Porkolab.
- 1C24. Stabilization of the Internal Tilt Mode in Field-Reversed Configurations by Edge-Layer Driven Rotation. L. C. Steinhauer.
- 1C25. Numerical Studies of Aspects of Small Scale Turbulence. A. B. Hassam.
- 1C26. Density-Gradient Driven Transport in Two-Temperature Magnetized Plasma. D. L. Galbraith and T. Kammash.
- 1C27. Millimeter-Wave Free Electron Laser Designs Based on Small Period Undulators. T. M. Antonsen, Jr., P. E. Latham, J. H. Booske, V. L. Granatstein, W. W. Destler, I. D. Mayergoyz, and E. Ott.
- 1C28. ASDEX Heat Pulse Propagation as a Forced Boundary Value Problem. A. Eberhagen, K. S. Riedel, G. Becker, O. Gruber, K. Lackner, O. Gehre, V. Mertens, and J. Neuhauser.
- 1C29. Canonical Maps for Toroidal Magnetic Fields. E. R. Tracy and A. H. Boozer.
- 1C30. Fishbone Oscillation Bursts Initiated by Fusion Alpha Particles. F. Porcelli, B. Coppi, and S. Migliuolo.
- 1C31. Debye Cloud in Magnetized Plasma. H. C. Huang, V. K. Decyk, and J. M. Dawson.
- 1C32. Ballooning Stability in Real Geometry Using Localized Equilibria. M. S. Chance.
- 1C33. Resistive MHD Calculations with the Hilo Code; Modified to Include the Full Set of Resistive MHD Equations. D. Monticello, R. Izzo, and W. Park.

1D POSTER SESSION

4:10 - 6:10pm Pacific Ballroom

- 1D1. Analytic Models of Ion Cyclotron Absorption. G. Francis, A. K. Ram, A. Bers, C. N. Lashmore-Davies, V. Fuchs, and L. Gauthier.
- 1D2. A 3-D PIC Code to Model the Tilt Mode in FRCs. E. J. Horowitz and D. E. Shumaker.
- 1D3. Why TMX-U did not Work. L. S. Hall.
- 1D4. Neoclassical Diffusion Coefficients in Tokamaks for Arbitrarily Aspect Ratio. C. S. Chang and Y. H. Oh.
- 1D5. Internal Kink Modes in the Large Larmor Radius Regime. F. Pegoraro, F. Porcelli, and T. J. Schep.
- 1D6. Performance and Optimization of Direct Implicit Time Integration Schemes for use in Electrostatic Particle Simulation Codes. R. J. Procassini, C. K. Birdsall, and B. I. Cohen.
- 1D7. Hot-Electron Equilibria in Electron Cyclotron Heated Plasmas. G. E. Guest and R. L. Miller.

- 1D8. Parametric Predictive Transport Analysis. J. C. Wiley, W. H. Miner, Jr., and D. W. Ross.
- 1D9. Electron Thermal Transport - A Comparison of Theory and Experiment. W. H. Miner, Jr., D. W. Ross, and J. C. Wiley.
- 1D10. MHD Stability Analysis of the Compact Ignition Tokamak (CIT). M. W. Phillips, A. M. M. Todd, and M. H. Hughes.
- 1D11. A Synthesis of the Quasi-Equilibrium and Resistive MHD Models. E. J. Caramana.
- 1D12. Physics Issues for a Second-Stability Tokamak Reactor. K. Evans, Jr. and D. A. Ehst.
- 1D13. Spectrally Evolved Resonant Diffusion. G. D. Kerbel.
- 1D14. Studies of Neutral-Beam Current Drive. R. S. Devoto, M. E. Fenstermacher, and A. A. Mirin.
- 1D15. Linear Analysis of FELs Employing Sheet Beams. P. E. Latham and T. M. Antonsen, Jr..
- 1D16. Calculation of Electron-Cyclotron Heated Distribution Functions in Tandem Mirrors. L. L. LoDestro and R. H. Cohen.
- 1D17. Calculation of Self-Consistent Potential with a Multi-Region Fokker-Planck Code. Y. Matsuda and L. D. Pearlstein.
- 1D18. An Efficient Numerical Scheme for 1-D Spectral 2-D Grid Point Resistive MHD Code. E. Uchimoto and J. D. Callen.
- 1D19. Ballooning and Interchange Stability of Plasmas with Equilibrium Flows. A. Bhattacharjee, A. Bondeson, R. Iacono, C. Paranicas, R. Gruber, and F. Troyon.
- 1D20. Energy Conservation and Wave Tunneling for Hermitian Differential Operators of Arbitrary Order. H. J. Kull, H. L. Berk, R. J. Kashuba, and P. J. Morrison.
- 1D21. Applications of Symbolic Computing to Computational Plasma Physics. N. T. Gladd.
- 1D22. Quasilinear Evolution of Ballooning Modes. K. S. Riedel.
- 1D23. Reduced Equations to Describe the Internal Kink Mode in Tokamaks. R. E. Denton, J. F. Drake, T. M. Antonsen, Jr., and R. G. Kleva.
- 1D24. Plasma Current Sustained by the Burning D-(3)He Fuel in a Field Reversed Configuration. T. Tajima, H. L. Berk, and H. Momota.
- 1D25. Computation of the Parallel Viscosity for Transport Purposes in Stellarators. W. D. D'Haeseleer, W. N. G. Hitchon, and J. L. Shohet.
- 1D26. Linear Kinetic Simulation of the $n=1$ Tilt Instability in the FRC. Z. Mikic and D. C. Barnes.
- 1D27. A Nonlinear Mechanism for Drift Wave Induced Particle Transport. A. M. Dimits, W. W. Lee, and J. A. Krommes.
- 1D28. Subgrid Scale Closures for MHD: Renormalized Transport Coefficients. Y. Zhou and G. Vahala.
- 1D29. Steady-State RFP Computations. J. P. Dahlburg, D. Montgomery, and G. D. Doolen.
- 1D30. Numerical Simulation of Drive Drift-Wave Turbulence. B. D. Scott, P. W. Terry, and P. H. Diamond.
- 1D31. Toroidal Effects on Shear Alfvén Waves Destabilized by Alpha Particles. J. W. Van Dam, G. Y. Fu, and M. N. Rosenbluth.
- 1D32. A Hybrid Vlasov-Fluid Model of Kinetic Ions and Massless Fluid Electrons. F. Kazeminejad, R. Sydora, J. M. Dawson, J. N. Leboeuf, and F. Brunel.
- 1D33. Steady States of the Kuramoto-Sivashinsky Equation. J-S. Kim and J. M. Greene.

TUESDAY MORNING 8:30 - 12:30pm

2A REVIEW SESSION -
 8:30am Pacific Ballroom
 Presiding: Herbert L. Berk

- 2A1. Free Electron Lasers. M. Rosenbluth.

2B ORAL SESSION - Alternative Concepts and Basic Theory
9:30am Pacific Ballroom
Presiding: Ronald H. Cohen

- 2B1. 1-D Transport Calculations for Z-Pinch Fibers. R. A. Nebel, H. R. Lewis, J. E. Hammel, D. W. Scudder, and P. Rosenau.
- 2B2. Oscillating Field Current Drive for the Reversed-Field Pinch. D. S. Harned, D. D. Schnack, H. R. Strauss, and R. A. Nebel.
- 2B3. Determining the Coils for Stellarators. P. Merkel.
- 2B4. Free-boundary Helias Stellarator Equilibria. S. P. Hirshman and P. Merkel.
- 2B5. Some Nonlinear Aspects of Intense Pulsed ECRH. B. I. Cohen.
- 2B6. Ion-Electron Energy Transfer Near the Separatrix in Diverted Tokamaks. F. L. Hinton.
- 2B7. Scaling Law for Energy Confinement in Turbulent Fluid Plasmas. E. Hameiri and A. Bhattacharjee.

TUESDAY AFTERNOON 2:00 - 5:00pm

2S SPECIAL SESSION - Honoring Marshall Rosenbluth's 60th Birthday
2:00pm Pacific Ballroom
Presiding: Chaun L. Liu

- 2S1. Resistive Instabilities in Toroidal Confinement. P. Rutherford.
- 2S2. Strong Plasma Turbulence. R. Sudan.
- 2S3. Universal and Not So Universal Instabilities. N. Krall.
- 2S4. Radiations in Plasma. B. Thompson.
- 2S5. Effects of Energetic Particles on Plasma Stabilities. H. Berk.

TUESDAY EVENING 7:00 - 11:10pm

2C POSTER SESSION
7:00-9:00pm Pacific Ballroom

- 2C1. Bootstrap Current in Nonaxisymmetric Toroidal Plasmas. E. C. Crume, Jr., K. C. Shaing, J. S. Tolliver, S. P. Hirshman, and W. I. Van Rij.
- 2C2. ECH-Driven Potentials in a Tokamak. R. H. Cohen, A. J. Lichtenberg, and M. A. Lieberman.
- 2C3. Optimal Shaped Cross-Section for Tokamaks Against External Kink Modes. S. P. Hakkarainen and J. P. Freidberg.
- 2C4. Stability Properties of Tokamaks with a Resistive Wall. S. W. Haney and J. P. Freidberg.
- 2C5. Anomalous Electron Energy Transport in Tokamaks. S. M. Mahajan, Y. Z. Zhang, and H. L. Berk.
- 2C6. Cross-Species Collisional Viscosity. C. T. Hsu and D. J. Sigmar.
- 2C7. Ideal Mercier Stability in 3-Dimensions. N. Dominquez, B. A. Carreras, V. E. Lynch, and S. P. Hirshman.
- 2C8. Nonlinear Absorption and Current Drive with Intense Microwave Pulses. W. M. Mevins, T. D. Rognlien, and B. I. Cohen.
- 2C9. A New Cellular Model for Magnetohydrodynamics. H. Chen and W. M. Matthaeus.
- 2C10. Energetic Particle Stabilization of Ballooning Modes in a Tokamak of Finite Aspect Ratio. M. E. Mauel, X-H. Wang, A. Bhattacharjee, and J. W. Van Dam.
- 2C11. Global ICRF Modeling in Large Non-Circular Tokamak Plasmas with Finite Temperature. E. F. Jaeger, D. B. Batchelor, H. Weitzner, and P. L. Colestock.
- 2C12. A Kinetic FRC Model. R. B. Webster, J. L. Schwarzmeier, H. R. Lewis, and C. K. Choi.
- 2C13. Theory of Trapped-Particle-Induced Resistive Fluid Turbulence. P. H. Diamond and H. Biglari.

- 2C14. Transition to the Second Region of MHD Stability in a Large Aspect Ratio Tokamak. M. H. Hughes, S. A. Sabbagh, A. M. M. Todd, M. W. Phillips, and G. A. Navratil.
- 2C15. Quantum Analysis of States Near a Separatrix. J. R. Cary, P. Rusu, and R. T. Skodje.
- 2C16. MHD Studies of the Internal Tilting Mode in a Field-Reversed Configuration (FRC). D. C. Barnes, R. Bishop, D. D. Schnack, and R. Milroy.
- 2C17. The Bifurcated Helical Equilibria. J-Y. Hsu.
- 2C18. Separatrix Effects on Kinetic Electromagnetic Toroidal Eigenmodes. G. Rewoldt, W. M. Tang, C. M. Bishop, and S. Hiroe.
- 2C19. Numerical Solution of Ampere's Law in Three-Dimensional Toroidal Domains. H. S. Greenside and A. H. Reiman.
- 2C20. Convergence Properties of a Nonvariational 3D MHD Equilibrium Code. A. Salas, A. H. Reiman, and H. S. Greenside.
- 2C21. Three-Dimensional MHD Equilibrium with Magnetic Islands. A. H. Reiman and H. S. Greenside.
- 2C22. Numerical Results on Field Errors in the Presence of RFP Equilibria. K. L. Sidikman, J. D. Callen, and R. A. Nebel.
- 2C23. Stability Properties of Shaped Tokamaks with Energetic Alpha Populations. D. A. Spong, D. J. Sigmar, and J. J. Ramos.
- 2C24. Transitions from Passing to Trapped in Stellarators and Rippled Tokamaks. C. L. Hedrick, J. S. Tolliver, and J. R. Cary.
- 2C25. Instabilities of an RFP with a Resistive Shell. G. Marklin.
- 2C26. Numerical Problems of Three-Dimensional MHD Simulations. C. K. Rowdyshrub and E. J. Caramana.
- 2C27. Applications of the BETA Equilibrium, Stability and Transport Codes to the Design of Stellarators. F. Bauer, O. Betancourt, P. Garabedian, and M. Wakatani.
- 2C28. Anomalous Transport in Toroidal Plasmas. A. H. Boozer.
- 2C29. ICRF Ponderomotive Force Effects on Tokamak Equilibrium and Stability. J. R. Myra, D. A. D'Ippolito, and G. L. Francis.
- 2C30. The Penetration of the Lower-Hybrid-Drift Instability to the Field Null in the Field-Reversed Configuration. A. G. Sgro.
- 2C31. Neutral Beam Injection and Plasma Diffusion in a Tokamak. H. Okuda and S. Hiroe.
- 2C32. Calculating the Self-Consistent Kinetic Tilting Eigenfunction for an FRC. H. R. Lewis, J. L. Schwarzmeier, and D. C. Barnes.
- 2C33. Ideal Stability Limits of DIII-D Equilibria. M. S. Chu, J. S. Kim, and L. Lao.

2D POSTER SESSION

9:10-11:10pm Pacific Ballroom

- 2D1. Profile Consistency: Global and Nonlinear Transport. B. Coppi.
- 2D2. Internal Kink Modes in Elongated Tokamaks with Flat Rotational Transform. J. J. Ramos.
- 2D3. Transport Theory for Fluctuating Electric Fields in Toroidal Plasmas. K. C. Shaing.
- 2D4. ICRF Modelling Studies for TFTR. C. K. Phillips, P. L. Colestock, G. W. Hammett, D. G. Swanson, D. B. Batchelor, E. F. Jaeger, D. N. Smithe, and P. Bonoli.
- 2D5. Bootstrap Current and Sawtooth Activity in Tokamak. M. N. Bussac.
- 2D6. Linear Mode Conversion and the Operator Theory of Wave Mechanics. R. O. Dendy.
- 2D7. Hot Electron Interchange Mode at Arbitrary Ion Cyclotron Frequency. Y. Z. Zhang, H. L. Berk, and T. Kamimura.
- 2D8. Numerical Properties of a Finite-Beta Gyrokinetic Plasma. W. W. Lee and R. D. Sydora.
- 2D9. Nonlinear Finite-Beta Gyrokinetic Equations. T. S. Hahm and W. W. Lee.
- 2D10. Neoclassical Effects on Resistive MHD Modes. M. Kotschenreuther and A. Y. Aydemir.
- 2D11. Hall Thermal Effects on Plasma Transport. P. N. Hu.
- 2D12. Optimized Matrix Solution Packages for Use in Plasma Physics Codes. A. E. Koniges and D. V. Anderson.
- 2D13. Speromak Heating by Lower Hybrid Pulses. E. C. Morse and R. Ziolkowski.
- 2D14. Thermal Diffusion in Turbulent Fluid Plasmas. S. Hamaguchi and E. Hameiri.

- 2D15. The Dynamo Effect at Low and High Beta. N. F. Otani and H. R. Strauss.
- 2D16. Status of TJ-II Device.
and
- 2D17. Nonlinear Effects on the Deposition of FEL Power in Alcator-C. A. H. Kritz, W. M. Nevins, G. R. Smith, and R. H. Cohen.
- 2D18. Optimization of the Bootstrap Current in Stellarators. V. E. Lynch, J. S. Tolliver, K. C. Shaing, and B. A. Carreras.
- 2D19. Ion Cyclotron Emission Calculations Using a 2D Full Wave Numerical Code. D. B. Batchelor, E. F. Jaeger, and P. L. Colestock.
- 2D20. On the Second Harmonic Layer of an Obliquely Propagating Extraordinary Wave in a Tokamak. K. Matsuda.
- 2D21. Surface Waves in a Magnetized Plasma Slab. D. Sultana, V. K. Decyk, and J. M. Dawson.
- 2D22. Effect of Poloidal Field on Ion Bernstein Waves. J. Milovich, B. D. Fried, and G. J. Morales.
- 2D23. CIT: Ideal MHD and Design. F. J. Helton, J. M. Greene, L. Lao, and R. D. Stambaugh.
- 2D24. Application of the Free Energy Principle $\Delta(2)F$ for Determining Tokamak Stability via Reduced Fluid Models. P. J. Morrison.
- 2D25. Spurious Excitation of Edge Lower-Hybrid Resonance by ICRF Couplers. E. Berro and G. J. Morales.
- 2D26. Stabilization of Long Wavelength Ballooning Modes by Poloidal Flow. H. Strauss and M. Hossain.
- 2D27. Ray Tracing Analysis of the Mode Converted Ion-Bernstein Wave in ICRF Heating. A. K. Ram and A. Bers.
- 2D28. Transport Simulations of the Compact Ignition Tokamak. D. P. Stotler, G. Bateman, and M. H. Redi.
- 2D29. The Effect of Peaked Profiles on Ignition. G. Bateman and D. P. Stotler.
- 2D30. Numerical MHD Simulation of an RFP with Resistive Wall. Y. L. Ho, S. C. Prager, and D. D. Schnack.
- 2D31. Short Wavelength Drift-Alfvén Vortices. D. Jovanovic.
- 2D32. MHD Stability Limits for Elongated Tokamaks. A. D. Turnbull, A. Roy, O. Sauter, F. Yasseen, F. Hofmann, W. A. Cooper, and F. Troyon.
- 2D33. Anomalous Transport due to Broken Symmetry. R. B. White and W. Stodiek.

WEDNESDAY MORNING 9:00 - 1:10pm

3A POSTER SESSION

9:00-11:00pm Pacific Ballroom

- 3A1. Two Dimensional Simulations of a Ramped Startup of a Toroidal Reversed-Field Pinch. D. A. Baker, K. M. Ling, S. C. Jardin, and N. Pomphrey.
- 3A2. Zero Dimensional CIT Ignition Studies with Drift Wave Turbulence Models. R. R. Dominguez and R. E. Waltz.
- 3A3. Motion Near the Separatrix of the Drift Wave Hamiltonian. I. Doxas, W. Horton, and H. L. Berk.
- 3A4. Inverse Problem for Incremental Synchrotron Radiation. N. J. Fisch.
- 3A5. Frequency Spectrum of Resistivity-Gradient-Driven Turbulence Due to Sheared Radial Electric Field. G. S. Lee, B. A. Carreras, and P. H. Diamond.
- 3A6. Gigaflop Speed Algorithm for 3D Plasma Equilibrium and Stability Problems. D. V. Anderson, A. R. Fry, R. Gruber, and A. Roy.
- 3A7. Plasma Simulations on the Mark III Hypercube Computer. P. C. Liewer, R. W. Gould, V. K. Decyk, and J. D. Dawson.
- 3A8. Second Harmonic Ion Cyclotron Resonance in a Tokamak. H. Weitzner and K. Imre.
- 3A9. Collector Sheath and Source Sheath in a Collisionless Finite Ion Temperature Plasma with Secondary Electron Emission and L. Schwager.
- 3A10. Boundary Conditions for the High Density Z-Pinch. A. H. Glasser.
- 3A11. Collisional Plasma Presheath. J. T. Scheuer and G. A. Emmert.
- 3A12. Neoclassical MHD Turbulence. O. J. Kwon and P. H. Diamond.
- 3A13. Computation of the Parallel Viscosity for Transport Purposes in Stellarators. W. D. D'Haeseleer, W. N. G. Hitchon, and J. L. Shohet.

- 3A14. Resistive Evolution of Plasmas with Imperfect Magnetic Surfaces. G. Miller.
- 3A15. MHD Equilibrium and Stability Considerations for CIT. J. Manickam.
- 3A16. Decimation of Betchov's Model of Quadratic Turbulence: Comparison with the DIA. T. Williams, E. Tracy, and G. Vahala.
- 3A17. Relativistic Considerations for Electron Cyclotron Current Drive in Tokamaks. V. S. Chan.
- 3A18. Simulation of Anomalous Transport in JET. A. Sykes.
- 3A19. Linear Theory of $m=1$ Tearing Modes. X-H. Wang and A. Bhattacharjee.
- 3A20. Reconnection in the Adiabatic Limit. M. Kress and A. A. Blank.
- 3A21. Field Error Reduction at the Poloidal Gap in a Reversed Field Pinch. R. W. Moses.
- 3A22. Nonlinear Relativistic Electron Orbits in the Presence of Intense ECH RF Fields. R. E. Aamodt and R. C. Davidson.
- 3A23. Resolution of Anomalous Thermal Transport Models. L. E. Sugiyama.
- 3A24. NOVA 2: A Kinetic-MHD Stability Code. C. Z. Cheng.
- 3A25. Fusion Alpha Particle Loss due to Ripple and MHD Modes. S. Zweben, R. B. White, and M. S. Chance.
- 3A26. Arbitrary Larmor Radius Calculation of the Interchange Instability. H. L. Berk and H. V. Wong.
- 3A27. Stable Access to Second Stability Regime in Tokamaks Using Radiofrequency Waves. A. Sen, P. K. Kaw, and A. K. Sundaram.
- 3A28. Low Frequency Axisymmetric Stability of Elongated Tokamaks. N. Pomphrey and S. C. Jardin.
- 3A29. The Use of CO(2) or Millimeter Radiation for the Detection of Alpha-Particles in a Fusion Plasma. L. Vahala and G. Vahala.
- 3A30. Full-Wave and Fokker Planck Studies of ICRF Plasma Heating. H. A. Romero and J. E. Scharer.
- 3A31. Theory of Clump-Wave Interactions in Trapped-Ion-Driven Turbulence. H. Biglari, P. H. Diamond, and P. W. Terry.
- 3A32. Electron Neoclassical Heat Conduction in Tokamaks Performed by the Ions. A. A. Ware.
- 3A33. Transport Simulations of Ohmic Pellet Experiments at TFTR, ASDEX and ALCATOR-C. M. H. Redi, W. M. Tang, M. Greenwald, D. K. Owens, G. L. Schmidt, and F. Wagner.

3B POSTER SESSION

11:10-1:10pm Pacific Ballroom

- 3B1. Questions and Issues on Parallel Processing I.
and
- 3B2. Questions and Issues on Parallel Processing II.
and
- 3B3. Eigenvalues Associated with Relaxed States of Toroidal Plasma. P. J. Hall, C. G. Gimblett, M. F. Turner, and J. B. Taylor.
- 3B4. Theory of $m(o)=1$ Modes in Regimes of Long Mean Free Path Relevant to Igniting Plasmas. F. Detragiache, B. Coppi, and F. Pegoraro.
- 3B5. Alpha-Particle Distribution in Ignition Plasmas. Y-P. Pao.
- 3B6. Nonlinear Simulations of Radiative Condensation and Reconnection Instabilities. G. Van Hoven, L. Sparks, T. Tachi, and D. D. Schnack.
- 3B7. Effects of Fast Ion Sources on Lower Hybrid Current Drive. M. D. Carter and D. B. Batchelor.
- 3B8. An Analytic, Large Aspect Ratio, High Beta Equilibrium. J. M. Greene.
- 3B9. Shape Optimisation of Low-Aspect Ratio Tokamaks. J. T. Hogan, J. A. Holmes, and E. A. Lazarus.
- 3B10. Inelastic Drift Wave Soliton Collisions and Transport. W. Horton and G. Biebuyck.
- 3B11. Scattering of Lower Hybrid Waves in Two Dimensions. W. Grossmann, R. Spigler, and M. Kress.
- 3B12. Numerical Simulation of Current Drive by Intense Microwave Pulses. T. D. Rognlien, W. M. Nevins, and R. H. Cohen.
- 3B13. Magnetic Plasma Surface Wave Instabilities. P. Amendt and H. U. Rahman.
- 3B14. Ion Heat Conductivity and Bootstrap Current in Low-Aspect-Ratio Tokamaks. C. O. Beasley, Jr., J. T. Hogan, W. I. Van Rij, and S. P. Hirshman.

- 3B15. Profile Consistency and Transport Modelling. R. Englade.
- 3B16. MHD Simulation of Density Limit Disruptions in Tokamaks. R. G. Kleva, R. E. Denton, and J. F. Drake.
- 3B17. The Effects of Rotation and Collisions on the Trapped Particle Mode in the Columbia Linear Machine. R. Scarmozzino, O. Mathey, and A. K. Sen.
- 3B18. Ion Temperature Gradient Driven Drift Waves: Particle Simulation and Theory. J. N. Leboeuf, G. S. Lee, D. R. Thayer, and P. H. Diamond.
- 3B19. Gaussian Closure Code and Direct Spectral Code Comparison for 2D, 2-Field Turbulent Relaxation. D. R. Thayer, G. Graddock, P. H. Diamond, and P. W. Terry.
- 3B20. Impurity Radiation Effects on Resistivity Gradient Driven Turbulence in the Edge Plasma. P. T. Katt, D. R. Thayer, P. H. Diamond, and V. Pham.
- 3B21. Eikonal Theory of Linear Mode Conversion in 4-Dimensional Plasma. L. Friedland and A. N. Kaufman.
- 3B22. Numerically Induced Stochasticity. A. Friedman and S. P. Auerbach.
- 3B23. Long-Time Behavior of Numerically Computed Orbits: Small Time-Step Analysis. S. P. Auerbach and A. Friedman.
- 3B24. Intrinsic Angular Momentum of Waves and the Torque of Linear Mode Conversion. H. Ye and A. N. Kaufman.
- 3B25. Destabilization of Global Compressional Alfvén Modes by a Hot Alpha Particle Species in an FRC. G. R. Burkhart, T. M. Antonsen, Jr., H. L. Berk, and V. Wong.
- 3B26. Relaxation of an Ablated Pellet Cloud Using the Grad Transport Model. M. Hossain, M. Kress, P. N. Hu, and A. A. Blank.
- 3B27. Ion Microstability of a Tara Neutron Source. M. J. Gerver.
- 3B28. Multiquadric Interpolation of Numerical Tokamak Equilibria. G. R. Smith, A. V. Kluge, and A. H. Kritz.
- 3B29. A Unified Theory of Ripple Transport in Stellarators. C. D. Beidler, W. N. G. Hitchon, W. I. Van Rij, S. P. Hirshman, and J. L. Shohet.
- 3B30. Development of a Microwave FEL Code Using Waveguide Modes. J. A. Byers.
- 3B31. Suppression of External Kink Modes in Tokamaks by RF Ponderomotive Effects. D. A. D'Ippolito.
- 3B32. The H-Mode, Counter-Injection, and Poloidal Rotation. R. J. Goldston, A. B. Hassam, and M. C. Zarnstorff.

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Physics Basis for the Compact Ignition Tokamak

R. R. Parker for the CIT Physics Team†

The CIT is a compact, high-field, high-current tokamak (typical design parameters $R = 1.6$ m, $a = 0.45$ m, $B = 10$ T, $I_p = 9$ MA) whose objective is to reach ignition, thereby permitting investigations of ignited tokamak regimes. Since the pulse length is expected to be on the order of $10\tau_E$, those phenomena associated with the energy confinement time-scale can be comprehensively studied. In particular, characterization and optimization of confinement of the released α -particle energy is a major goal of the experiment. Phenomena which evolve on a slower time-scale, for example those associated with resistive equilibration of the current density profile or long pulse plasma wall issues can be only partially addressed.

The baseline design incorporates a divertor, a choice which is based both on relevancy to future machines and also on the potential for confinement optimization. Both 0-D and 1-D analyses of confinement reveal that ignition is achievable under “L-mode” confinement only by careful control of the plasma profiles, assuming conventional tokamak operational limits apply. Optimization of the position of the PF coils, mainly located outside the TF magnet, results in energy efficient designs which, however, tend to favor high elongation, $\kappa \gtrsim 2$ and moderate triangularity, $\delta \gtrsim 0.3$. In this case a separatrix naturally forms near the plasma boundary. Some internal coils are nevertheless necessary in order to control the x-point or “strike-point” on the divertor plates, as well as to assist the wall in stabilizing axisymmetric modes.

The stability of CIT discharges and the β -limit are subjects of continuing and active investigation. The β -limit depends strongly on the assumed pressure and current profiles: optimized profiles yield stable values of β well above that required for ignition (assuming H-mode scaling), while more realistic current profiles have broad, nearly shearless regions in which high- n ballooning and low- n infernal modes limit the pressure gradient and degrade confinement. An additional concern is the low value of $q_j \equiv J_\phi(0)/\langle J_\phi \rangle$ which tends to destabilize external kinks even at moderate values of q_ψ .

Additional topics of physics interest include plans for auxiliary heating, startup scenarios, and divertor design. These subjects will be discussed in this review talk as time permits.

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Fully Toroidal MHD Nonlinear Studies of the $m = 1$ Fast Sawtooth Crash *

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Recent experimental results on both TFTR¹ and JET² at low β have shown sawtooth drops which take place on a very rapid time scale. These sawtooth drops occur in two steps. The first step is a shift of the hot central region of the plasma helically outward, and the second is a thermal decay of this hot region to form a relatively flat temperature profile at the end of the sawtooth drop. The rapid time scale is inconsistent with the Kadomtsev reconnection model which involves a resistive MHD mode and the low β precludes an ideal MHD mode generated with conventional monotonic profiles being responsible, since these modes are stable at low β . Wesson,³ however, has pointed out that certain types of non-conventional safety factor (q) profiles can destabilize ideal $m = 1$ modes at low β and can cause the initial shift of the plasma interior. In addition, these profiles give a very sharp stability boundary which is necessary to explain the required fast time scale "trigger" needed to excite these precursorless modes. Fully toroidal resistive MHD nonlinear calculations have been done using two of these non-conventional profiles: 1) a flat profile where q is very close to unity across the entire central region of the plasma; and 2) a hollow profile with the safety factor value at the magnetic axis being greater than that just outside the plasma interior. Both types of profiles evolve nonlinearly on about the right time scales to be responsible for the initial shift seen during the sawtooth drops. The hollow profiles give a range of time scales close to the experimental values. The flat profiles, on the other hand, give scales at the upper end of those observed experimentally. Results of these studies will be presented.

* 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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Ideal Internal Kink Modes and Rapid Sawtooth Crashes *

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Ideal internal kink modes are investigated, in connection with rapid sawtooth crashes, using nonlinear, compressible full MHD equations in toroidal geometry. Present-day tokamaks exhibit rapid sawtooth crashes not adequately explained by the Kadomtsev reconnection process. In particular, JET has reported crashes that occur on an ideal MHD time scale¹. Wesson has suggested that a pressure driven $m = 1$ ideal kink mode could be the responsible mechanism². For typical q -profiles, such modes tend to be stabilized by toroidal effects. They are unstable only for $q < 1$, and because of favorable average curvature, require β_p values much higher than those at which rapid crashes are observed³. In low shear systems, however, we demonstrated linearly and nonlinearly that pressure driven modes can account for many features of rapid JET-type crashes using high- β reduced MHD equations in toroidal geometry, and compressible, full MHD equations in cylindrical geometry⁴. Here we extend these studies to toroidal geometry using nonlinear, compressible full MHD equations. The salient features of our findings are as follows:

1. For low shear systems with $q_0 \geq 1$, ideal kink modes are observed for all $\beta \geq 0$. For $\beta \simeq 0$, these are non-resonant, $J_{||}$ -driven modes destabilized by toroidicity for $q < 1$ ⁵. The growth rates scale as $\gamma\tau_{Hp} \sim \epsilon^3$, with $\gamma \gg \gamma_{tearing}$ for $\beta = 0$, $\epsilon = 1/3$, and $S = 10^8$.
2. The mode is further destabilized by finite- β . For the experimentally relevant values of $\epsilon\beta_p \simeq 0.1$, $\gamma\tau_{Hp} \simeq O(10^{-2})$. Nonlinear studies at these parameters indicate that rapid crashes in JET can be explained by these modes.
3. Since line-bending energy is minimized, not by a uniform displacement that vanishes in a boundary-layer at the rational surface, but by keeping $k_{||}^2$ small in the region of interest, these modes are highly sensitive to the details of the q -profile. As in our earlier studies⁴, we find that slight modifications in $q(\psi)$ for $q > 1$ can act as a trigger for the crash.
4. For comparable values of $\epsilon\beta_p$, fully toroidal nonlinear calculations differ somewhat from the cylindrical ones. The hot core that is displaced off-axis at the start of the crash does not eventually extend fully around a cold "bubble", but forms a semi-circle. Such a helical deformation can be the source of successor oscillations sometimes observed in JET.

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TEARING MODES IN TOROIDAL GEOMETRY

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Abstract

The separation of the cylindrical tearing mode stability problem into a resistive resonant layer calculation and an external marginal ideal mhd (Δ') calculation is generalised to toroidal geometry. The general structure of this separation is analysed and the marginal ideal mhd information (the toroidal generalisation of Δ') required to discuss stability is isolated. This can then, in principle, be combined with relevant resonant layer calculations to determine tearing mode growth rates in realistic situations. Two examples are given: the first is an analytic treatment of toroidally coupled ($m = 1, n = 1$) and ($m = 2, n = 1$) tearing modes in a large aspect ratio torus; the second, a numerical treatment of the toroidal coupling of three modes through finite pressure effects in a large aspect ratio torus. In addition we discuss the use of a coupling integral approach to determining the stability of coupled tearing modes. Finally, the possibility of using initial value resistive mhd codes in realistic toroidal geometry to determine the necessary information from the ideal mhd marginal solution is discussed.

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Modelling of Temperature Profiles and Transport Scaling
in Auxiliary Heated Tokamaks

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ABSTRACT

The temperature profiles produced by various heating profiles are calculated using local heat transport models. The models take the heat flux to be the sum of heat diffusion and a non-diffusive heat flow. This form is consistent both with theory and with local measurements of heat transport which show there is a significant diffusive component. Two models are developed analytically in detail: a heat pinch or excess temperature gradient model with constant coefficients and a nonlinear heat diffusion coefficient (χ) model. Both models predict weak ($\leq 20\%$) temperature profile responses to physically relevant changes in the heat deposition profile -- primarily because the temperature profile is a double integral of the heating profile. The model predictions are shown to agree with JET data for a variety of heating profiles ranging from peaked on axis, to approximately flat (NBI at high density), to localised off-axis (ICRH). The modest temperature profile responses that result from the models clarify why temperature profiles in many tokamaks are often characterised as exhibiting a high degree of "profile consistency".

Global transport scaling laws are also derived from the two models. The nonlinear model with $\chi \propto dT/dr$ produces the energy confinement time scaling with input power $\tau_E \propto P_{in}^{-1/2}$. The constant heat pinch or excess temperature gradient model leads to the offset-linear law for the total stored energy W with P , i.e., $W = \tau_{inc} P + W(0)$. It also provides definitions for the incremental energy confinement time $\tau_{inc} = \eta(3ab/4\chi)$, the heating efficiency η , and the energy offset $W(0)$.

Considering both the temperature profile responses and the global transport scaling, the constant heat pinch or excess temperature gradient model is found to best characterise the present JET data. Finally, new methods are proposed for interpreting auxiliary heating data in terms of these local transport models.

3D Computational Study of Electron Cyclotron Heating and Current Drive*

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Auxiliary heating of plasmas in the electron cyclotron range of frequencies (ECRF) is particularly attractive because of its ability to provide localized heating and current drive¹ at radii readily adjustable by varying the toroidal magnetic field. Beyond simple global heating and current drive of the plasma, these characteristics provide a means for exploring the radial dependence of heat transport² and determination of effects of current profile on MHD instabilities.³

With these important uses in mind, a new 3D bounce-averaged Fokker-Planck/Quasilinear code has been constructed to be used for detailed prediction of and comparison with experiment. Using the Kerbel-McCoy code⁴ to solve on a radial array for the 2D (in velocity) bounce-averaged electron distribution consistent with an ECRF energy deposition model incorporating quasilinear damping, we obtain the toroidally averaged electron distribution everywhere in the tokamak.

This code has been used to explore ECRF current drive particularly as applied to the DIII-D tokamak for a range of ECRF launching scenarios. New effects discovered with this code are a reduction of current drive efficiency assuming inside launch of the fundamental X-mode, and an increase of efficiency for outside launch of fundamental O-mode and second harmonic X-mode, at experimentally relevant input powers. The decrease in efficiency in the inside launch case results from competition of the Fisch-Boozer mechanism¹ with the Ohkawa trapping mechanism.⁵ In outside launch cases this competition is alleviated by relativistic effects on the wave-particle resonance, leading to increased current drive efficiency as a result of plateau formation and subsequent damping further out in the tail.

The 3D distributions afford detailed predictions of soft x-ray and electron cyclotron emission spectra, facilitating comparison with experimental data.

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RADIATIVE CONDENSATION INSTABILITIES IN TOKAMAK
EDGE PLASMAS

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The nature of the radiative condensation instability¹ and its role in causing Marfes and edge density fluctuations in tokamaks has been investigated. The instability is driven by the density dependence ($\sim n^2$) of the local radiative emission rate — a decrease in the local temperature causes a sound wave to flatten the local pressure and thus increases the local density and radiation rate, which further reduces the temperature. The onset of axisymmetric, large-scale instabilities (Marfes) can be inhibited by parallel thermal conduction² but is more strongly controlled by the thermal flux from the central plasma into the edge.³ This thermal flux ties the Marfe threshold to the density limit, as is experimentally observed.

The growth rates and thresholds of helical condensation instabilities, which approximately track the local magnetic field, have also been calculated. A broad spectrum of modes are typically unstable in tokamak edge plasmas, especially at high density where radiation rates are large. The nonlinear growth and saturation of these helical instabilities are also being studied. The instability is driven by parallel rather than cross field plasma flow so that the usual $\mathbf{v}_\perp \cdot \nabla$ nonlinearities which saturate pressure driven instabilities at small amplitude [$\sim (kL_n)^{-1}$] are absent. As a consequence, the instability saturates at large amplitude and is a plausible source for order one density fluctuations often measured in the tokamak edge plasma. Calculations of the nonlinear growth and saturation of a single helical mode in a sheared magnetic field will be presented.

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

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HOT ELECTRON STABILIZATION OF BALLOONING MODES IN TOKAMAKS

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ABSTRACT

Rosenbluth, Tsai, Van Dam and Enquist¹ have demonstrated with a model equilibrium that ballooning modes can be stabilized in a tokamak by introducing an anisotropic highly-energetic trapped-particle population. They derive a ballooning mode equation from the generalized kinetic energy principle and then use an analytic circular-cross-section infinite-aspect-ratio equilibrium to study the stabilizing properties of the hot particles on a flux surface. An important constraint on the hot particle beta arises in their analysis; the bounce averaged drift of the hot particles cannot reverse directions. This proves to be a serious obstacle to demonstrating hot particle stabilization on all flux surfaces of numerically generated equilibria.

We extend the above model by considering numerically generated finite-aspect-ratio equilibria and attempting to stabilize all flux surfaces simultaneously by suitable choice of a hot electron anisotropic pressure. To facilitate access to the second stability regime, we consider a circular cross section with an aspect ratio of ten. We find that global stabilization of ballooning modes is possible but difficult; the non-drift reversal constraint imposes profile limitations on the core plasma pressure, the anisotropic pressure, and the safety factor. We provide a prescription for determining the maximum allowable anisotropic pressure for any equilibrium.

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SHERWOOD THEORY MEETING 1987

**Dynamic Global Access to Second Stability
in Auxiliary Heated Tokamaks****G. Y. Fu, J. W. Van Dam,**and M. N. Rosenbluth*

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It is well known that ideal ballooning modes limit the beta value that can be attained in a tokamak operating in the usual first stability parameter regime, but that the existence of the second stability regime could allow for the possibility of high-beta operation. It has also been shown that various methods (e.g., the introduction of highly energetic particles, the average magnetic well in a tokamak, or finite gyroradius effects) can stabilize ballooning modes on individual flux surfaces for low values of the shear, thus providing a route by which to access the second stability regime.

In this work, we investigate the dynamical process by which a plasma confined in a tokamak can globally evolve toward second stability under the application of large auxiliary heating. We employ a simple one-dimensional time-dependent transport model, with a large but finite anomalous diffusion coefficient induced by ideal ballooning instability, and numerically solve in time self-consistently for the pressure profile and the magnetic field rotational transform, in the large aspect ratio limit. A small Laplacian-squared term (e.g., due to FLR effects) in the transport equation prevents numerical instability that would otherwise lead to singular steepening of the pressure gradient. Near the edge of the plasma, the problem of access to second stability can be analytically recast in the form of a shock solution for a stationary Sagdeev-type potential. The numerical and analytical results indicate that higher heating power is required, as the ballooning mode-induced anomalous transport increases, in order for the plasma to be able to attain a stable high-beta, steady-state profile.

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EQUILIBRIUM ALFVEN FLUCTUATIONS DUE TO DISCRETE PARTICLE EFFECTS*

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Magnetic fluctuations in the Alfvén frequency range are studied using the test particle scheme. The source driving the fluctuations is modelled as a single test particle current arising from the thermal motion of the plasma particles. The dynamic response of the plasma is included in the form of a macroscopic equation of motion to describe the magnetohydro-dynamic modes in a compressible uniform plasma.

Using the test particle scheme, fluctuation amplitudes and spectra in the Alfvén frequency range have been evaluated for three types of the polarization of the source current: (i) Guiding center current parallel to the equilibrium magnetic field (ii) Perpendicular current arising from magnetic moments of the particles (iii) Cross field current due to stochastic spatial diffusion. It is found that only the shear Alfvén waves are excited by type (i) and that the resistivity is necessary to cause wave excitation as well as wave damping. The typical fluctuating-to-equilibrium magnetic field ratio for this case is of the order of 10^{-9} . The result found with the second type is qualitatively different in that only the magnetosonic waves are excited. The type (iii) can excite both of these branches and is limited in magnitude by the relevant diffusion coefficient which gives rise to the source current. Numerical values for these cases will be presented and the effects of shear will be discussed.

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CHAOTIC FIELD LINE RESISTIVITY AND VISCOSITY
AND THEIR EFFECT ON THE TEARING MODE

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In order to estimate the effect of a symmetry-breaking perturbation on the nonlinear growth of the tearing mode, we compute the effective resistivity and electron viscosity due to chaotic magnetic field line trajectories near the separatrix of the original island. This chaotic behavior is, roughly, due to overlap of secondary resonances. Actual transport coefficients are computed numerically and are compared with quasilinear theory based upon the amplitudes of the secondary resonances. Transport coefficients are difficult to compute (and to define unambiguously) because of the presence of cantori and resonances;¹ the diffusion of a field line trajectory is impeded by the presence of these structures on a "time" scale roughly comparable to a correlation time. Preliminary results on the growth of the tearing mode are presented.

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

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SYNCHROTRON RADIATION ABSORPTION COEFFICIENT IN RELATIVISTIC PLASMAS

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The calculation of phenomena associated with the resonant interaction between relativistic electrons gyrating around magnetic field lines (cyclotron frequency $\omega_b = -e \cdot B_0 / m$) and electromagnetic radiation (wave frequency ω) is in general very complicated. One of the reasons for this is the strong temperature, frequency and directional dependence of the coefficients describing this interaction: radiation emissivity $j(\omega, \theta, T)$ and absorption coefficient $\alpha(\omega, \theta, T)$.

The ordinary approach is to calculate the absorption coefficient from the dielectric tensor obtained from linearized Vlasov kinetic equation transformed to $(\mathbf{k}, \omega)$ space by Laplace-Fourier method. The result is an integral, the evaluation of which is a very demanding task as it requires special mathematical care in addition to a considerable numerical effort. For practical purposes empirical formulae were derived which have poor accuracy and smoothed out the resonant profile of the absorption coefficient.

An alternative approach is suggested by an analogy regarding the plasma-wave particle interaction. It can be shown that the conventional Fourier-Laplace approach in kinetic theory to derive the dielectric tensor is equivalent to a single particle treatment in space-time based on the plasma response concept and using an impulsive motion perturbation method.

We actually confirmed that a single particle radiation treatment gives an absorption coefficient equivalent to that derived from kinetic theory. In this paper the calculation of the absorption coefficient depends on an integral with a smooth integrand. This not only facilitates numerical integration considerably, but suggests also that further analytical treatment may yield simplified and yet precise representations.

It is shown that for wave propagation perpendicular to the magnetic field a simple and highly accurate formula can be found for the absorption coefficient by purely analytical manipulations, without making any of the common assumptions needed in other computations. For arbitrary directions of propagation this result was extended by introducing two fitting functions with a priori arbitrary dependence on temperature and wave frequency. The appropriate generalization was found empirically, and the fit parameters were optimized. Results are given in analytical and graphical form, and their accuracy is demonstrated by comparison with the result of a numerical evaluation of the exact formula.

LOWER HYBRID WAVE PROPAGATION IN A TOKAMAK*

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In axisymmetric geometry Maxwell's equations with an arbitrary conductivity tensor are reduced to two second order partial differential equations for two generalized electromagnetic potentials. When the conductivity tensor is specified to be the cold plasma model for a tokamak with an exact, low beta, Soloviev equilibrium, the resultant system is solved numerically. For modest sized tokamaks with not too many wavelengths included in the device, the numerical solution is satisfactory. Energy absorption is modelled by the addition of a small skew hermetian tensor to the hermetian dielectric tensor. It is verified directly that the wave patterns and energy absorption are independent of the details of the skew hermetian tensor. The integral version of the Poynting-Energy Absorption theorem is used to monitor the accuracy of the numerical calculation.

In addition to the usual lower hybrid resonance surface, another resonance surface near the magnetic axis is found. Heating does not occur everywhere on these surfaces, but only at special points on them. In addition heating occurs along characteristics leaving these points. Simulations corresponding to small tokamak parameters are exhibited.

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Compressibility and Temperature Effects in Toroidal MHD *

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In order to study the full MHD linear stability and nonlinear evolution of plasmas in toroidal geometry, the computer code FAR has been developed at Oak Ridge National Laboratory. In its existing formulation, FAR assumes incompressibility ($\vec{\nabla} \cdot \mathbf{v} = 0$) and a resistivity profile which is constant in time. At present, FAR is being modified to include the effects of compressibility and temperature evolution, both of which may be important to the understanding of MHD phenomena in toroidal geometry. In this paper we will present our approach to the modelling and formulation of these effects together with some initial results for the $n = 1$ mode.

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SHERWOOD THEORY MEETING 1987

Alfvén Wave Heating With a Single Impurity Species *

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With the inclusion of a radially varying impurity charge profile, a new two-ion hybrid resonance in the plasma interior and an ordinary Alfvén resonance near the plasma edge are generated. The latter gives rise to the Cold Plasma Surface Alfvén Eigenmodes^{1,2} (SAE). Numerical results show that, in contrast to the pure plasma, certain SAE dissipate substantial energy near the two-ion hybrid layer. Analytically we find that, magnetohydrodynamically, Kummer's functions describing the fields in the two-ion hybrid layer and scale length of wavefunctions in between these two resonances strongly affect the distribution of energy deposition. These are sensitive to the mode numbers, curvature, and gradient of $\omega/\omega_{c\alpha}$ terms. Analytical results obtained from the derived dispersion relation agree with the antenna-driven numerical solutions.²

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Evaluation of the Slowing Down Tail Enhanced Neoclassical Alpha Particle Energy Flux

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The non-Maxwellian slowing down tail formed by the energetic alpha particles produced in a fusing tokamak is shown to substantially enhance the neoclassical radial energy loss of alphas. The retention of the pitch angle scattering of the energetic tail alphas by the background ions results in neoclassical fluxes which have not been evaluated previously. Of particular interest is the energy flux associated with the tail alphas since it is found to be much larger than that of the ash alphas for comparable densities. Fortunately, only a small fraction of the alpha fusion power is lost because of this enhanced energy diffusion so that most of the alpha energy is deposited in the background plasma.

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ENERGY CASCADES IN ALMOST TWO-DIMENSIONAL TURBULENCE*

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A theory has been presented¹ concerning strong turbulence of a strongly anisotropic magnetized plasma,² where the dissipationless nonlinear dynamics do not depend on the parallel coordinate, and parallel mode coupling occurs only through weak dissipation or excitation. This situation models drift waves, for example. Enhanced dissipation is predicted as the weak coupling makes highly damped, large $k_{\parallel}$ modes accessible via a direct cascade in $k_{\parallel}$. The theory calculates the effective dissipation rate, which can be used in a two-dimensional code to evolve large-scale modes, accounting for the cascade of energy to small scales.

To test the theory, a direct three-dimensional simulation has been developed. This code has only a small number of modes^{3,4} in each perpendicular plane (at $k_{\parallel} = \text{constant}$), but has good resolution along $k_{\parallel}$, typically 128 modes. We compare the theoretical prediction of energy cascade rate, steady-state parallel spectrum, and effective damping rate with simulation results. Preliminary results are presented.

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PONDEROMOTIVE STABILIZATION OF HIGH-N BALLOONING MODES IN TOKAMAKS*

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In order to reach the second stability region in tokamaks, it is necessary to stabilize the ballooning modes during the transition period of β increase. Interest in RF ponderomotive stabilization has been expressed for this purpose.

We use the energy principle with ponderomotive terms¹ to determine stability threshold, with particular attention to the so-called side-band terms. The calculation makes use of no eikonal approximation for the RF field in the equilibrium configuration, but exploits the ballooning mode formalism in the high-n (toroidal mode number) limit, when the ballooning mode perpendicular wavelength is between the ion gyroradius and the macroscopic length scales (in particular, the RF field decay length). It is shown that the side bands are nearly electrostatic, and are always destabilizing (in the regime $\omega_{RF} \geq \Omega_i$). Estimates of necessary RF power is given, and feedback control² is investigated.

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* Work supported by College of Engineering and Theory Center, Cornell University.

Axisymmetric ideal MHD equilibria with flow

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The equilibrium of plasmas with flow is studied using the axisymmetric steady-state ideal MHD equations. We present numerical results showing that the relative effects of flow on high- β equilibria are much greater than on low- β . Asymptotic expansions are performed to determine the vertical magnetic field necessary for equilibrium. A larger magnetic field is always needed to support the rotating plasma, whereas the shift of the magnetic axis may be enhanced or diminished due to flow. Arguments using homotopy techniques indicate it is not possible to have an equilibrium with an imbedded transition region.

Application of the PIES Code to CIT Equilibria

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The three-dimensional PIES code¹ has been developed for both stellarator and tokamak studies. An important application of the code to tokamak problems is the study of the effect of increasing the pressure on the magnetic field ripple associated with there being a finite number of toroidal field coils. The vacuum magnetic field can be approximated well in an R, ϕ, Z coordinate system by

$$\mathbf{B} = 2I \nabla [\phi + K_1(N) I_0(NR/R_c) \sin N\phi],$$

with I_0 and K_1 Bessel functions of the second kind; I is the total current in the central legs of the N toroidal field coils, which are treated as having an infinite ellipticity and shape such that the return current lies on a surface at R_c and is sinusoidal in $N\phi$. We first compare the PIES two-dimensional equilibrium solutions obtained by neglecting the magnetic field ripple with the results from the PEST code² for the CIT Design parameters. This provides a useful calibration of the PIES code. We then introduce a toroidal ripple and compare the magnetic field modulation in a force-free configuration with a high- β one.

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Equilibrium and Stability of the Davis Diverted Tokamak*

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The Davis Diverted Tokamak (DDT) is a small toroidal device which will be constructed at the University of California, Davis and located at LLNL. This tokamak will have a major radius of 50 cm. The vacuum chamber will be race-track shaped cross section with a vertical diameter of 64 cm and a horizontal diameter of 32 cm. Poloidal divertor coils will be placed at the top and bottom outside the vacuum chamber. The plasma current will be approximately 10 KA with an axial toroidal magnetic field of up to 10 KG at the plasma center.

Numerical studies will be presented of equilibrium and MHD stability. Both passive and active stabilization are being studied. The code TSC [1] is used to determine the optimum positioning of passive poloidal coils to reduce the growth rate of the axisymmetric mode.

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ANODE PLASMA EXPANSION IN MAGNETICALLY INSULATED DIODES

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and

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In recent experiments¹ in magnetically insulated diodes a fast anode plasma expansion has been observed. In the present paper we discuss various mechanisms that could give rise to such fast expansion. In the context of the fluid theory we find that the electron heating imposes a severe restriction on the expansion velocity, requiring higher plasma densities than observed. It has been suggested² that charge-exchange processes may be a source of a fast neutral-filling of the diode gap. Followed by the ionization, this process can lead to a fast plasma expansion. In this model we compute plasma parameters and find them in a rough agreement with the observation.

This research has been supported in part by NSF Grant ECS-8314488.

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Coupling of Ion Bernstein Wave from a Loop Antenna*

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Efficient ion heating by Ion Bernstein waves (IBW) has been obtained in JIPPT-II-U,¹ PLT,² and Alcator C.³ Heating appears to be due to nonlinear mechanisms and is most significant near $\frac{3}{2}\Omega_i$, and heat absorption is mostly by bulk ions. The ion Bernstein waves were launched by a loop antenna aligned parallel to the toroidal field. However, the coupling of Ion Bernstein waves by loop antenna has not been investigated. In the present paper, the coupling theory of such a configuration is studied. The sensitivity of coupling to varying edge plasma conditions is investigated. The effect of low frequency turbulence on IBW will be presented

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THREE DIMENSIONAL STUDIES OF LOWER HYBRID WAVE LAUNCHING

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We present recent results in the development of a 3-D numerical simulation of lower hybrid wave launching in realistic tokamak geometry. An SAIC simulation tool, ARGUS, is used as the central element of this study. ARGUS is a multi-dimensional hybrid simulation code which couples self-consistently with various physics models including surface physics, radiation, etc. We have shown previously¹ how a model tokamak vacuum chamber, flush mounted slow wave (grill) launcher and metallic limiter may be modelled with the ARGUS code. Initial results obtained with a square cross-section, taken for convenience, indicate significant distortion of the radiation pattern due to geometry and interference effects. We will present the latest attempt at modelling circular cross-section chambers plus a more realistic grill similar to that used in the ALCATOR C lower hybrid studies.

¹W. Grossmann, L. Seftor, A.T. Drobot, Twenty-Eighth Annual Meeting of the Division of Plasma Physics, American Physical Society, November 3-7, 1986.

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SHERWOOD THEORY MEETING 1987

**New Developments in the Theory of
Ion Temperature Gradient Driven Turbulence***

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Recent experimental results¹ suggest that ion temperature gradient driven turbulence (η_i -modes²) may be an important cause of anomalous heat transport. Previous theoretical studies³ of η_i -driven turbulence utilized the assumption that the width of the envelope of the lowest eigenmode is characteristic of the radial correlation length of the turbulence. However, recent (2-D) particle simulations indicate that higher radial eigenmodes are strongly excited. Such fluctuations are broader and more oscillatory than the lowest mode.

Here, we consider the role of higher radial eigenmodes. An improved cascade model allowing for coupling in k_θ , k_z , and k_r is formulated. The role of this nonlinear radial coupling is assessed in terms of its effects on fluctuation levels and scalings. Preliminary results indicate that the level of anomalous transport may be somewhat larger than previously calculated.

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Experiences Parallelizing a 3-D MHD Code*

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The three-dimensional, resistive, MHD initial-value code TEMCO has been reprogrammed to allow multiprocessing. Virtually all sections of the main time loop have been rewritten. In the process of doing so, a comparison of the CFT and CIVIC compilers vis a vis vectorization has been carried out. Most key areas of the time integration module have been multitasked, including the coefficient computation, leapfrog advance and semi-implicit advance. An analysis of multitasking efficiency and cost for typical Reversed Field Pinch and Spheromak applications is presented.

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Simulation of Poloidal Current Heating in a High Beta Tokamak

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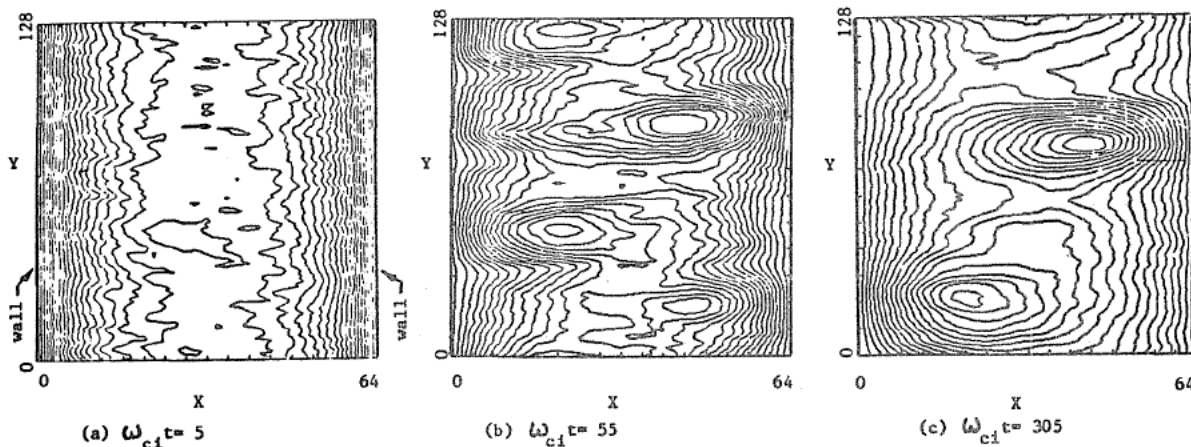
A two-dimensional resistive MHD code with a self-consistent boundary condition on the poloidal flux function has been used to simulate the Columbia experimental high beta device-HBT. Three different types of heating schemes are simulated. The following important physical effects have been found:

- 1). Parallel heating leads basically to an adiabatic compression in minor radius. The total average β decreases as the toroidal field increases.
- 2). In the screw pinch, the plasma is heated by both toroidal plasma current and adiabatic compression. The large toroidal plasma current results in low q of the final tokamak state.
- 3). During antiparallel heating, the plasma is first compressed to the so called "magnetic pressure-balance state" in which the toroidal field inside and outside plasma have equal magnitude but are in opposite directions. Large poloidal current densities can be induced to heat the plasma to a high β state. It is selected as a potential scheme for high β tokamak formation.

For high β tokamak formation, major radial force balance is important. Two major forces, i.e. the plasma pressure expansion and the $\vec{J}_p \times \vec{B}_t$ force are analyzed in the simulation. The pressure expansion force is a monotonously increasing force while the $\vec{J}_p \times \vec{B}_t$ force is a time-varying pulse. A carefully programmed vertical field is designed to counter the major radial force imbalance. With this vertical field programming, a very high β equilibrium has been achieved in the numerical simulation.

Transport induced by a Crossed-Field Sheath¹ - K. THEILHABER,
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We are studying transport across the magnetic field in a plasma bounded by conducting boundaries with the aim of modelling plasma behavior in the vicinity of the limiters and walls of a fusion device. Our approach is to use the two-dimensional, bounded particle simulation code "ES2" as a tool for the investigation of edge effects, in an idealized geometry which retains, however, the essential features of the physics of the edge plasma. Thus far, our simulations have revealed that the bounded plasma is subject to the so-called "Kelvin-Helmholtz" instability² an instability maintained by the sheared electric field which is induced by the presence of the material walls. This instability is seen to saturate into large and stable vortices, which can be described by some variant of the so-called "Hasegawa-Mima" equations³. These vortices exist in the vicinity of the walls, and drift parallel to their surfaces. An important feature of these structures is that they continuously convect particles to the walls, at a rate much greater than that induced by collisional diffusion. This property seems tied to the mutual interaction of the vortices. In the code "ES2", we have modelled volume ionization of neutrals by a uniform electron-ion pair creation in the simulation region, and this results in a steady state, in which the linear edge instability, the nonlinear fluid dynamics of the vortices, and the nonlinear dynamics of the particles scattered by the vortices all balance each other. We consider this configuration a first crude model of the edge behavior induced by the boundaries. A movie will be shown, showing vortex formation and the time-dependent depletion of the density profiles.



Equipotential contours for a bounded plasma simulation, at three different times. The system was initially filled with a uniform electron-ion plasma, and left to evolve self-consistently. 41000 particles of each species were initially in the system. The magnetic field is rigorously perpendicular to the plane of the simulation, and the boundaries are conducting, absolutely absorbing surfaces. The plasma parameters are such that, $m_i/m_e = 40$, $\omega_{pi}/\omega_{ci} = 2$, $\omega_{pe}/\omega_{ce} = 0.3$, $\beta_e = 1.0$, $\lambda_{de} = \lambda_{di} = 3.3$, $\beta_i = 6.3$.

In the final state, the right-hand vortex is moving upward, the left-hand vortex downward. In the presence of volume ionization, this final state is a steady-state, with electrons and ions assuming triangular density profiles.

¹This work supported by U.S. Department of Energy Contract No. FG03-86ER53220.

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NONTHERMAL ION CYCLOTRON EMISSION FROM OPTICALLY THICK PLASMAS*

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The emission spectrum observed during Ohmic and ICRH discharges, when the ICRF antennas are in reception mode, provides valuable information about the physics of ion cyclotron absorption and radiation and about the physical properties of the plasma (energetic ion or electron tails and fusion reaction products).^{1,2} Hot, dense thermonuclear plasmas become optically thick to ion cyclotron radiation and in order to unfold the complex emission spectrum analytical and plasma simulation methods must be used.

To study the radiation emission and absorption from nonthermal ion distributions in a nonuniform magnetic field, a 2-1/2 D (x - z , v_x - v_y - v_z) electromagnetic particle simulation model is used. A slab model is assumed with toroidal field variation, $B \approx B_0(1-x/R_0)\hat{z}$, periodic boundary conditions in the z -direction and plasma-vacuum in the x -direction. Absorbing radiation conditions are used outside the plasma slab, however, with conducting boundaries at $x=0$, L_x enhancement of radiation due to wall reflections can be studied. The radiation spectrum is determined outside the plasma slab by storing various field components and Fourier analyzing in time. Thermal and nonthermal perpendicular ion distributions (tail-Maxwellians) were initialized. It is found that nonthermal radiation peaks are generated at equally spaced cyclotron harmonics for the latter case. The dependence of this emission spectra on various parameters as well as on concentration of various ion species will be discussed.

*Work supported by DOE and done in collaboration with H. Naitou.

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1987 SHERWOOD THEORY CONFERENCE
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**Analysis of Lower Hybrid RF Stabilization of
Sawteeth in the Alcator C Tokamak***

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Recent experiments¹ on the Alcator C tokamak have demonstrated the stabilization of sawteeth via the injection of lower hybrid waves, using a current drive waveguide phasing ($+\pi/2$). A mechanism for sawtooth stabilization is proposed which involves changes in the toroidal current density profile $J_{\parallel}(r)$, due to RF current generation. Two possible modifications are being investigated. The first is a reduction in $J_{\parallel}(0)$ and a subsequent increase in the on-axis safety factor $q(0) > 1$. The second, more subtle modification is a "flattening" of $J_{\parallel}(r)$ near the $q(r) = 1$ surface, due to RF current generation at that point. Recent studies² using a resistive and fully toroidal MHD code have indicated that the resulting $q(r)$ profiles [i.e., $dq(r)/dr$ is reduced near $q(r) = 1$] could lead to a stabilization of the $m = 1$ mode. The possible changes to $J_{\parallel}(r)$ due to RF current generation and electron plasma heating are studied using a simulation model for lower hybrid current drive and heating.^{3,4} Model results relevant to the Alcator C experiment will be presented.

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- * Work supported by the U.S. Department of Energy DE-AC02-78ET51013.

STABILIZATION OF THE INTERNAL TILT MODE
IN FIELD-REVERSED CONFIGURATIONS
BY EDGE-LAYER DRIVEN ROTATION

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Multipole stabilization of the rotational mode in field-reversed configurations (FRC), demonstrated five years ago, has made it possible to generate FRCs that remain grossly stable for a lifetime determined by resistive decay. These lifetimes range from 50 to 100 or more Alfvén transit times (based on the length of the FRC) in many experiments. However, FRCs are also well-known (theoretically) to be MHD-unstable to the internal tilting instability, which is expected to produce rapid disruption of the configuration. The inverse growth rate of this mode is approximately the Alfvén transit time, and therefore the mode should have been observed. A possible explanation for the nonobservance of the mode is that ion kinetic effects strongly reduce the growth rate so that the mode does not have time to develop during the lifetime of the FRC.¹ Another possibility is that FRC rotation can stabilize the internal tilt.² A recent theory by Ishida and Momota is based on a two-fluid (cold electrons) MHD model of a rotating FRC where the rotation is set by the ion diamagnetic drifts in the interior of the FRC (i.e. inside the separatrix). Plasma rotation has usually been ignored in previous analyses of the tilting instability. They predict stabilization of the internal tilt for sufficiently large elongation (length/diameter): the elongation required for stability increases linearly with plasma radius. Their theory has been extended to account for the more rapid rotational speed driven by the ion drifts in the edge layer. This leads to much stronger stabilization, requiring only that the elongation exceed a value of order unity (independent of the plasma radius). This possibility has sweeping implications for future large FRC experiments (such as LSX, presently being constructed at Spectra Technology) as well as for reactor applications.

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NUMERICAL STUDIES OF ASPECTS OF SMALL SCALE TURBULENCE

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Some aspects of transport from small scale turbulence are examined with the help of a numerical pseudospectral code. Attention is focussed on the ideal and resistive interchange mode as a model problem. The aspects that are examined include the following: (i) the proposition that the anomalous mass diffusion from electrostatic fluctuations, D_p , is of order $\gamma/k_\perp^2$; (ii) the idea that heat transport from a combination of magnetic flutter and parallel heat conduction may exceed D_p even if the mode is dominantly electrostatic; and (iii) the aspect of cylindrical turbulence that $D_p \sim \gamma/k_\perp^2$ holds over a global scale even if modes are radially localized provided there is sufficient mode overlap.

Work supported by U.S. Department of Energy.

Density-Gradient Driven Transport in
Two-Temperature Magnetized Plasma

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Classical diffusion across magnetic fields driven by density gradients in hot plasmas is a problem that has been considered by many authors because of its application to many areas in plasma physics. In most cases, however, only particle diffusion in one-temperature plasmas has been considered. And even when the interacting species were allowed to have unequal temperatures, the energy diffusion resulting from the density gradients was not calculated. Even in the case of single-temperature particle diffusion, there are disagreements among existing results. In this paper, expressions for classical particle and energy diffusion across magnetic fields for multi-temperature plasmas are derived from basic principles. The results are then compared with those most often quoted in the literature.

MILLIMETER-WAVE FREE ELECTRON LASER DESIGNS
BASED ON SMALL PERIOD UNDULATORS*

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We have initiated a program to develop millimeter wave FEL's for RF plasma heating using moderate energy (200-750 keV) electron beams interacting with a planar magnetic wiggler field in the 2-10 mm range. At these low beam energies a number of interesting problems associated with beam space charge arise. In particular, we have considered the following: (1) the confinement and stability of the sheet beams required for high power operation with small period wigglers. In this configuration, the beam should be stable on short time scales; however, resistive wall instabilities may deconfine the beam or cause it to filament. (2) We have analyzed the three dimensional mode structure of the radiation and self fields for the sheet beam configuration. Indications are that operation in the Raman regime may be limited by uniformity of the beam density. However, with a thin beam the current density at which the Raman regime is entered is higher than predicted by one dimensional theory. (3) In order to enhance efficiency we are considering tapering wiggler parameters. Self field effects limit the rate of taper and gain per wiggle period achievable and set a minimum to the length of the interaction region if a particular efficiency is desired.

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ASDEX HEAT PULSE PROPAGATION AS A FORCED BOUNDARY VALUE PROBLEM

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V. MERTENS, J. NEUHAUSER AND the ASDEX and NI Teams

THE ELECTRON HEAT CONDUCTIVITY, χ_i IMMEDIATELY AFTER A SAWTOOTH CRASH IS INVESTIGATED FOR A VARIETY OF DIFFERENT PARAMETERS. TO DETERMINE χ_i , we solve a forced initial value problem outside the mixing radius. The forcing parameter is the temperature evolution at the inner boundary point. The experimentally measured ECE signal at the first point outside the mixing radius is used as the input. χ_i is then determined by fitting the temperature evolution of the other electron cyclotron emission channels outside the input channel.

This approach has several important advantages over the standard method of fitting the arrival time of the peak of the pulse to a theoretically initialized perturbation. The region inside the mixing surface where the conductivity may be anomalously large, is excluded from consideration. The arrival of the peak depends primarily on the conductivity between the input radius and the output radius. Thus local values of χ_i are determined. No assumptions on the position of the $q=1$ surface or the radial redistribution of energy are necessary. The conversion of magnetic energy into heat is automatically taken into account. Finally, the ECE measurements give a time history of the heat pulse at a few spatial locations and the method makes effective use of this information.

The method is tested on a standard Ohmic discharge with the following parameters, $Q(A)=3.3$, $T(0)=1075\text{eV}$, $N=2.4 \cdot 10^{13}$, $Z=1.3$. THE INPUT channel is at 18.1cm and the fit channel at 25.6 cm. Ten sawteeth are averaged over the sawtooth period. The period is 13ms, the crash time is 1ms, the amplitude is 90eV, and the peak of the pulse arrives at $r=18.1\text{cm}$ 1.65ms and at 25.6cm at 2.65ms. In practice, the pulse has four characteristic parameters, the arrival of the peak, the amplitude of the peak and slope of the temperature rise and the slope of the decay. We are able to fit the first three parameters with a constant χ_i of 70cm/ms. A radially increasing χ_i gives a slightly better fit. The decay of the pulse depends on both the radial variation of χ_i and the boundary condition. The corresponding power balance χ_i is 12cm/ms at 18cm and 17cm/ms at 25cm.

The standard calculation for a Kadomtsev initialization gives $\chi_i=38\text{cm/ms}$, however the amplitude is significantly smaller, the exact amount depends sensitively on the position of the mixing radius, and the shape is greatly distorted. A possible explanation is that immediately after the crash, the heat conductivity is greatly enhanced in the center and that the plasma is in thermal equilibrium with the new flat profile.

Canonical Maps for Toroidal Magnetic Fields

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The magnetic field line equations are well known to have a Hamiltonian structure¹. This is a result of the fact that the magnetic field can be represented in the following form:

$$\vec{B} = \nabla\psi \times \nabla\theta + \nabla\phi \times \nabla\chi$$

where ψ , θ , ϕ and χ are well behaved single-valued functions of position. Magnetic field lines are the integral curves of this vector field. These lines are constructed by integrating the following pair of differential equations:

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

These equations are Hamiltonian with χ the Hamiltonian and ϕ the time. This implies that the mapping at a period - which takes the initial position of a field line and maps it to its position after one or more passes around the torus - is a canonical transformation. This in turn implies that a generating function exists which generates this transformation for an arbitrary number of passes.

A method for constructing the single pass generating function is described. The relationship between the multipass generating function, which can be determined from the single pass function, and stochasticity will be studied.

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FISHBONE OSCILLATION BURSTS INITIATED BY FUSION ALPHA PARTICLES

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According to the model presented in Refs. 1 and 2, the fishbone instability in the presence of energetic ions is related to an $m^0 = 1$ mode oscillating at the core-plasma diamagnetic frequency ω_{di} when the following instability conditions are met: (a) the core-plasma poloidal beta β_p exceeds the threshold value for the excitation of pressure-driven $m^0 = 1$ modes in the toroidal plasma (however, the ideal-MHD internal kink instability is rendered marginally stable by core-ion Larmor radius effects); and (b) a resonant mode-fast-ion interaction can take place, which provides the needed "viscous" dissipation for the release of the mode excitation energy in the plasma pressure gradient.

Compact ignition experiments that have been recently proposed have the ability to cover a relatively wide range of β_p , so that plasma regimes can be attained where condition (a) is satisfied. At birth, α -particles produced by DT reactions with energy of 3.5MeV do not interact efficiently with the $m^0 = 1$ mode as the characteristic frequencies associated with their periodic motion are much larger than ω_{di} . Thus, condition (b) can be satisfied when a significant fraction of the alphas has slowed down to energies of the order of 300-400keV, the relevant mode-particle interaction involving trapped α -particles that precess around the torus due to the curvature and the gradient of the confining magnetic field. In this case, the scattering of the resonant alphas produced by the excited mode would not significantly affect the plasma energy balance; on the contrary, it may have the beneficial effect of reducing the fusion ash in the thermal plasma bulk. On the other hand, the containment of newly-born α -particles may also be degraded, once the fishbone instability has been initiated by the slowed-down alphas. In fact, the fluctuating magnetic field associated with this mode may induce a significant nonresonant drift of the banana orbits, due to a breakdown of the constraints that keep the radial position of the banana centers fixed. Work supported in part by the US Department of Energy.

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DEBYE CLOUD IN MAGNETIZED PLASMA*

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A subtraction technique has been used in our particle simulation to study the plasma response to a gyrating test particle. The Debye cloud around the test particle is measured. From this, one has a visual and quantitative picture of wave emission in a magnetized plasma. One can measure as well the corresponding drag force. Interestingly, the force has components perpendicular as well as antiparallel to the particle motion. Results will be presented of a parameter study as the imposed magnetic field and Larmor radius of the test particle are varied. A beginning at a theoretical formulation of the problem has been made.

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BALLOONING STABILITY IN REAL GEOMETRY USING LOCALIZED EQUILIBRIA*

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A better understanding of the effect of realistic tokamak geometry on MHD stability can be gained by extending the calculations of Greene and Chance.¹ There, the underlying features of the first and second region of ballooning instability were studied effectively and efficiently by applying the ballooning mode equation on equilibria which were generated as self-consistent (i.e., with the Grad-Shafranov equation) perturbations from an arbitrary given equilibrium. That study is now extended by imbedding the calculations in equilibria with a variety of shapes, aspect ratios, safety factors, etc. One important benefit from this is the ability to generate realistic counterparts of the well-known but modelistic s - α diagram of Connor, Hastie, and Taylor. The results will hopefully lead to better guidance in selecting shapes and profiles in the design of future tokamaks.

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

RESISTIVE MHD CALCULATIONS WITH THE HILO CODE;
MODIFIED TO INCLUDE THE FULL SET OF RESISTIVE MHD EQUATIONS*

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The Hilo code¹ has been modified to include all toroidal terms of the compressible MHD equations. The resulting equations are solved by the partially implicit method and thus have a time step restriction imposed only by the shear Alfvén wave. A discussion of this method and the boundary conditions will be presented. Also presented will be results of the nonlinear calculations of TFTR and TEXTOR like profiles.

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ANALYTIC MODELS OF ION CYCLOTRON ABSORPTION*

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We present results from an effort aimed at analytical descriptions of basic wave processes involved in ion-cyclotron heating of a tokamak plasma with one or two ion species. In particular we derive an analytic form of the transmission coefficient for the mode conversion region based upon the solution of an appropriate first-order differential equation; we show that the transmission and reflection coefficients as well as the transmission and mode-conversion coefficients, each pair, can be obtained adequately from the solution of second-order differential equations; and thus the power dissipated can also be obtained. In addition we derive a new analytic description for the transition from strong to weak mode conversion. We compare our results with those obtained from various numerical codes. The scaling of this type of heating to regimes of high density, magnetic field, and temperature for ignition experiments will be discussed.

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⁺⁺Project Tokamak, I.R.E.Q. Varennes, Quebec, Canada

A 3-D PIC Code to Model the Tilt Mode in FRCs*

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QN3D, a 3-dimensional, hybrid, Particle-in-Cell (PIC) Code is presented. It treats electrons as a cold, inertialess fluid and solves the electromagnetic fields in the Darwin limit. The resulting equations are non-linear and they are solved by functional iteration with no linearizing assumptions.

This code has been designed to model the tilt mode in Field Reversed Configurations. This mode is unusual in that MHD codes have predicted violent growth but experiments have seen no growth at all. We believe that the finite ion orbits which are categorically ignored by MHD codes provide the essential stabilization. If this is the case, then larger experiments might see the tilt mode as the ion orbits become less significant in relation to the other relative scale lengths.

In the course of development, test problems have been done to assess the code. To date, single particle motion, normal mode propagation and the rigid rotor instability have been done. For the final application, QN3D will be given an initial equilibrium from EQV, a 2-D (r-z) Vlasov equilibrium code. This equilibrium code assumes that the ion distribution is a given function of the Hamiltonian and the canonical angular momentum and the electrons are modeled as a cold, inertialess fluid as in QN3D.

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WHY TMX-U DID NOT WORK*-- Laurence S. Hall, *Lawrence Livermore National Laboratory*. We have shown that in TMX-U the bounce-average passing-electron model of conventional tandem mirror theory is incorrect. Conventional theory ignores the scattering of passing electrons by instabilities at a collisionless interface although such instabilities are known to explain the intimately-related Langmuir paradox [1]. Moreover, experiment confirms that TMX-U is intensely unstable at high frequencies [2]. The role of electron instability in decoupling the properties of the plug from the central cell is of great importance. As a result the description of TMX-U must be considerably modified. The experiment is reinterpreted in terms of a corrected model, which in turn finds little importance to plugging as an assessment of overall TMX-U behavior. Plugging potential profiles are found independently of the presence or absence of sloshing ions, or at least of the "sloshing" angular distribution characteristic. Much of the important behavior relates to energy loss through the electron channel, which appears to be relatively unhelped by the added complexity of tandem geometry over the geometry of a simple single-cell mirror. Experimental evidence in support of our view is cited at length.

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NEOCLASSICAL DIFFUSION COEFFICIENTS IN TOKAMAKS
FOR ARBITRALLY ASPECT RATIO

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Neoclassical diffusion coefficients have been evaluated near the unit aspect ratio in a circular concentric flux-surface geometry. By taking the small parameter to be the difference between unity and the aspect ratio, the behavior of diffusion coefficients has been determined as the aspect ratio decreases from unity toward zero. By combining this result with the large aspect ratio calculation of Rosenbluth, Hazeltine, and Hinton[1], which determined the behavior of diffusion coefficients as the aspect ratio increases from zero toward unity, the new formula for the neoclassical diffusion coefficients have been found. The new ion thermal conductivity is not much different from the result of Chang and Hinton[2]. However the new electrical conductivity is about 30% larger than that given by Hazeltin, Hinton, and Rosenbluth[3].

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INTERNAL KINK MODES IN THE LARGE LARMOR RADIUS REGIME

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The dispersion relation of resistive $m^0 = 1$ internal kink modes is derived for plasma regimes where ion kinetic effects determine the width of the singular layer. In these regimes the ion Larmor radius, ϱ_i , is larger than both the resistive and the inertial scale lengths. Full Larmor radius terms in the ion kinetic response are obtained through an appropriate model developed in Ref. 1. Collisional fluid equations in the isothermal limit are assumed for the electrons.

The mode growth rate depends on the value of the normalized beta parameter, $\hat{\beta} \equiv \beta(L_s/r_p)^2$, where $\beta = 8\pi p/B^2$, L_s is the magnetic shear length, and r_p is the pressure scale length. For values of $\hat{\beta} \leq 1$, the mode growth rate is enhanced with respect to the fluid result. On the other hand, when $\hat{\beta} > 1$ and ϱ_i is arbitrary, the fluid growth rate is recovered to lowest order. This is best understood by noticing that $\hat{\beta} = (\omega_* r_0 / \omega_A \varrho_i)^2$, where ω_* is the diamagnetic frequency (we assume $\omega_* = \omega_{*i} \sim -\omega_{*e}$), $\omega_A = v_A/L_s$ is the Alfvén frequency, and r_0 is the radius of the surface where the magnetic winding index $q = 1$. When $\hat{\beta} > 1$, the fluid ion Larmor radius effect related to finite values of ω_* is dominant. The mode structure is also affected by kinetic Larmor radius effects.

The relevance of the present theory to current and near future ignition experiments will be discussed.

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PERFORMANCE AND OPTIMIZATION OF DIRECT IMPLICIT TIME
INTEGRATION SCHEMES FOR USE IN ELECTROSTATIC PARTICLE
SIMULATION CODES*

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Implicit time integration schemes allow for the use of larger time steps than do conventional explicit methods, thereby extending the applicability of kinetic particle simulation methods. We will present the results of a study of the performance and optimization of two such schemes which are used to follow the trajectories of charged particles in an electrostatic, particle-in-cell plasma simulation code. The two direct implicit schemes, known as the C_1 and D_1 schemes, were chosen for their desirable properties which allow for the simulation of phenomena at frequencies much lower than the plasma or cyclotron frequencies. These properties include i) the relaxation of $\omega\Delta t$ constraints on the stability of the method, ii) strong damping of high-frequency modes for which $\omega\Delta t > 1$, and iii) second-order accuracy of the methods in the simulation of low-frequency phenomena for which $\omega\Delta t < 1$.

The formulation and optimization of the direct implicit schemes will be outlined, followed by a short discussion on the incorporation of these schemes into the electrostatic particle code. The results of a numerical stability study will also be presented. This study was based upon the freely expanding plasma slab model, which was run for various combinations of the important simulation parameters $\omega_{pe}\Delta t$, $\Delta x/\lambda_{De}$ in the range $0.1 \leq \omega_{pe}\Delta t \leq 200.0$, $0.1 \leq \Delta x/\lambda_{De} \leq 100.0$, excluding the region for which $v_e\Delta t/\Delta x > 1/2$. The degree of numerical heating or cooling (lack of energy conservation) was used as a quantitative measure of the numerical stability of the scheme. The results indicate that the D_1 scheme possesses a much larger region of parameter space over which energy is well conserved, than does the C_1 scheme. A locus of stable operating points is suggested by the data for each of the schemes.

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HOT-ELECTRON EQUILIBRIA IN ELECTRON CYCLOTRON HEATED PLASMAS

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ABSTRACT

We have used a relativistic Fokker-Planck model of electron cyclotron heating¹ to examine the basic physical processes that govern the distribution in energy of hot electrons in representative ECH plasmas. The model exhibits in a clear way the ECH runaway phenomenon that occurs when the RF heating rate exceeds the Coulomb cooling rate, as well as the non-adiabatic loss of high-energy electrons in small, low-field experiments and the synchrotron radiation cooling of energetic electrons in large, high-field experiments. Selective heating of relativistic electrons using ordinary-mode or upper off-resonant illumination in high-Q cavities provides a useful measure of control over the equilibria predicted by the Fokker-Planck model. Extensive exploration of these underlying processes in a one-dimensional model provides a useful guide to efficient use of the more computationally intensive two-dimensional model, CQL.²

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SHERWOOD THEORY MEETING

Parametric Predictive Transport Analysis*

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Recently, some of the techniques used in the expert system community have been applied to parametric analysis of problems described by a relatively few parameters, such as solving for the roots of a dispersion relation.¹ We have attempted to incorporate some of these ideas into a tool for comparing various theoretical transport coefficients in a predictive transport code against a database of experimental results. This problem has a large number of parameters and an imprecisely defined output. The tool consists of an integrated package of software which: (1) extracts experimental data from one of the experimental databases,^{2,3} (2) selects a transport model from a database of theoretical models, (3) builds an input file for a transport code, and (4) executes that code. The code solves the transport problem a number of times attempting to minimize a cost function representing the goodness of fit between the experimental data and corresponding computed profiles. A key component of the system is a formal language that describes the transport models to be used, the parameters to be varied, and the norms used to generate the cost function as well as the graphical output desired. The input language is described in terms of a context free grammar. A compiler for the language has been developed using the Unix tools *lex*⁴ and *yacc*⁵. This language allows cost functions to be built using norms measuring the fit between any of the experimental data sets and any of the possible computed profiles while varying any number of the many input parameters. Initially, the system has been used to examine some of the electron thermal transport coefficients proposed by the IPSPG panel.^{6,7}

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SHERWOOD THEORY MEETING

**Electron Thermal Transport —
A Comparison of Theory and Experiment****W. H. Miner, Jr., D. W. Ross and J. C. Wiley*Fusion Research Center
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Recent work in predictive transport simulation for the CIT has emphasized the need for self-consistent theoretical transport models. In order to obtain a level of confidence in these theoretical models, their validity must be determined via some method of comparison with the current database of experimental data. The purpose of this work is to demonstrate a procedure¹ for doing such an evaluation. For this demonstration, only electron thermal transport will be considered in order to focus on a few current theoretical models.

Although the mechanism for electron thermal transport in the plasma interior is unknown, present theory points to electrostatic driftwaves in the case of low beta discharges and electromagnetic, resistive ballooning modes in the case of high beta discharges as the most likely candidates.² Since the theories will be compared to experimental data from the TEXT database³ only the low beta theories will be considered. Two theoretical transport models that have been chosen for this demonstration. First is the drift wave model of Domingues and Waltz⁴ which includes a model for the effects of low-m tearing modes. The second theoretical model is the "profile consistent" drift wave model of Tang.⁵

The fundamental method used here to compare theory with experiment is to determine a norm by which the difference or error between the theoretically determined profiles and the experimental data can be measured. Having established a norm, the free parameter in the model, usually a multiplicative constant, will be varied in an attempt to minimize the error. This result will then be compared with the usual procedure of comparing experimentally measured and theoretically predicted confinement times.⁴

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MHD Stability Analysis of the Compact Ignition Tokamak (CIT)*

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Various aspects of stability of the proposed CIT device are presented. The CIT design is characterized by high magnetic field and high current. Presently, design parameters are $B_T = 9.67$ T, $I = 9.00$ MA, $R = 1.6$ m, $a = 0.48$ m, $\kappa = 1.9$, $\delta = 0.30$, $q_0 = 0.80$, $q_{\text{edge}} = 2.7$. The high current, low q_{edge} , leads to a broad region of low shear in the center presenting several stability problems. The central region is invariably unstable to either Mercier or ballooning modes making it unable to support a significant pressure gradient. In addition, the low shear central region can be infernal mode unstable. This is a concern since the α -particle contribution to the pressure is expected to peak in the center. With optimized pressure profiles betas up to and exceeding the Troyon beta limit can be achieved. However, these profiles are generally peaked near the edge. A study of current and pressure driven instabilities mapped out in β vs q_{edge} space is presented. The q profiles are given by steady state solutions to the magnetic diffusion equation. The pressure profile is independently optimized with respect to local ballooning modes. Studies varying κ and δ will also be shown. Results indicate increasing the triangularity while keeping current constant raises the first stable region beta limit.

Progress in computer code development has been made in several areas. Optimum pressure profiles with respect to infinite- n ballooning modes can now be obtained with just a few iterations. This was done by including the effect of changes of the local field line equilibrium in the ballooning equation. The limits of the first and second stable regions p'_{crit} can now be determined and a local $S - \alpha$ diagram can be generated. Also, the flux coordinate equilibrium code has been modified to calculate free boundary equilibrium. This will simplify the poloidal field coil design and can be used to determine the sensitivity of x-point positioning.

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A SYNTHESIS OF THE QUASI-EQUILIBRIUM AND RESISTIVE MHD MODELS*

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A common long timescale assumption in studying the evolution of fusion plasmas is to neglect inertia in the momentum equation (quasi-equilibrium approximation). Then the time behavior of the plasma magnetic field configuration can be found on the resistive, and other transport, times. The velocity is implicitly determined by the time varying forces that are exactly in balance (an elliptic equation). However, instabilities on a faster hybrid timescale ($\tau_A^\alpha \tau_R^{1-\alpha}$) can spontaneously develop. In the reversed field pinch (RFP) such instabilities are always necessary to maintain the toroidal field reversal, even though the plasma persists on the long timescale. Thus a model that accounts for both these effects is necessary. We develop such a model in terms of flux coordinates and adiabatic dependent variables primarily for RFP studies, although possible tokamak applications are discussed. All equations are transformed in terms of flux coordinates based on the mean poloidal magnetic field and new "adiabatic" dependent variables are derived. This results in, among other things, an evolutionary equation for $q(r)$ formally containing an " α effect" without any spatial scale assumptions. Preliminary numerical results of this model in the quasi-linear limit will be presented.

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PHYSICS ISSUES FOR A SECOND-STABILITY TOKAMAK REACTOR*

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ABSTRACT

As part of the Tokamak Power Systems Study (TPSS) effort, Argonne has recently completed a loose, conceptual design of a reactor involving a number of innovative and consequently more speculative concepts. Among these concepts is operation in the second stability regime. The primary reason for using second-stability-regime, MHD equilibria is, of course, higher β , but as a group, they have properties that are somewhat different from the more conventional equilibria in the first stability region and hence require different choices in a reactor design. For example, high rather than low aspect ratio and indentation on the inboard side seem to be preferred. This paper will present some of these different characteristics and show the TPSS design choices that have been made as a result of them.

There is a great deal of uncertainty yet concerning equilibria in the second stability regime. The major question is whether they exist at all, since there is no empirical evidence to this effect. There are also questions on the theoretical side as to whether they should exist. Theoretically produced equilibria have tended to have one or more questionable assumptions, among these being perfectly conducting walls at the plasma boundary, non-zero currents and large pressure gradients at the boundary, neglect of low- n modes, and highly-shaped pressure profiles. In addition, for a reactor design it is necessary to know the upper limit of β , and this is poorly mapped in the literature, seeming, in fact, to be a function of the code used. This paper will also discuss these problems and the progress that has been made in understanding them.

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Spectrally Evolved Resonant Diffusion

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Wave-particle interaction in the standard quasilinear theory of resonant diffusion in inhomogeneous magnetic fields is generalized by the introduction of incoherence through the mitigative presence of another interacting wave or particle. The effect is a sort of resonance broadening which can be represented mathematically by an appropriate gyrophase diffusion kernel in the trajectory integral.

Until recently the numerical evaluation of these generalized orbit integrals had been problematic and success was limited to special cases. A new technique has now been developed which allows the global development of numerical representations of these integrals. The method utilizes a relationship between these integrals and the solutions of a certain parabolic system, the initial and boundary data for which derive from an asymptotic analysis of the fully coherent interaction.

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Studies of Neutral-Beam Current Drive(*)

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We have been studying neutral-beam current drive with neoclassical (bootstrap) effects in large tokamaks. We use two codes for these studies: (1) The FPT code [1] numerically solves the square-well 2-D Fokker-Planck equations as a function of radius for circular cross-sections in cylindrical geometry. Beam deposition is determined with a Monte Carlo computation which includes toroidal effects and allows for focusing in the horizontal and vertical planes. (2) The MUMAK code [2] carries out 0-D energy and particle balance with steady state non-inductive current drive for arbitrary cross-sections. Both codes use fixed radial density and temperature profiles. In the FPT calculation the beams are aimed to maintain the safety factor $q > 1$ throughout the plasma. Studies have focused on a next-generation Tokamak - TIBER - with the following properties computed from MUMAK: $R_0 = 3$ m, $B_{t0} = 5.55$ T, $I_p = 10$ MA, elongation (κ) = 2.4, triangularity (δ) = 0.4, $a = 0.83$ m, $N_e = 0.88 \times 10^{20}/\text{m}^3$, $T_e = 16$ keV, $T_i = 31$ keV, $E_{\text{beam}} = 500$ keV. The poloidal beta for this configuration with these parameters is of order unity. The FPT calculations are carried out using this same value of beta-poloidal because this is one of the main parameters governing the fraction of bootstrap current. We compute normalized current drive efficiencies for fairly broad density and temperature profiles both with and without bootstrap effects. The fraction of bootstrap current increases substantially for more peaked density profiles.

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LINEAR ANALYSIS OF FELs EMPLOYING SHEET BEAMS*

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We have analyzed the linear stability of the short wiggler period, low voltage, sheet beam FEL under development at the University of Maryland. Such an FEL, operating in the millimeter range, is a possible candidate for RF plasma heating. We have found that finite beam thickness modifies the dispersion relation by reducing the effective electric field of the space charge wave. This phenomenon raises the density which defines the transition from the Compton to Raman regimes.

Two cases have been considered in detail: a cold laminar beam of arbitrary thickness in which the equilibrium self fields exactly balance the strong focusing field of the planar wiggler, and a warm beam whose betatron oscillation frequency is assumed to be much greater than the growth rate. Both models produce the same dispersion relation in the limit of a thin beam, and we have analyzed this dispersion relation extensively. In the case of the warm beam model we can apply variational techniques to obtain a dispersion relation if we make some assumptions about the form of the equilibrium distribution function.

An additional problem that we have considered is the effect of beam density variation in the long transverse direction. In the Raman regime we find that the growth rate can be reduced substantially due to the fact that the plasma wave will only be resonant at particular points along the beam. The scaling of this effect with density variation will be presented.

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Calculation of Electron-Cyclotron Heated Distribution Functions in Tandem Mirrors*

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Electron-cyclotron resonant heating (ECRH) is used in the plug cell of a thermal-barrier tandem mirror to assist in the formation of the (electron) barrier and (ion) plugging potentials. ECRH is applied at both the plug and barrier locations, and is typically strong enough to render the electron distribution far from Maxwellian.

We have developed approximate forms for the hot-electron distribution function f in the strong-ECRH limit. Numerical results indicate that, in the regions of phase space in which electrons are confined to the endcell, f varies most rapidly near the intersection with the trapped-passing separatrix, over an energy scale that is short compared with characteristic endcell energies and diffusion coefficient variations, and is instead set by the boundary condition, i.e. the central-cell temperature T_c . We also observe that in the limit of strong ECRH, the kinetic equation can be written approximately in the form of a two-dimensional diffusion equation with a diagonal diffusion tensor. By approximating the ECRH and collisional diffusion coefficients as constants and rescaling variables, the kinetic equation reduces to Laplace's equation. We obtain solutions with boundary conditions appropriate to the cases described below, then reintroduce unscaled variables and the variation of the coefficients.

We apply this procedure to cases where the particles passing to the center cell are assumed Maxwellian, but particles confined to the plug and/or barrier regions are dominated by various combinations of the plug and barrier ECRH, and find that the hot-electron distribution function can be expressed in terms of the plasma dispersion function. We also consider a case where the plug ECRH is strong enough to dominate over collisions in the center cell for passing electrons (but electrons trapped in the center cell remain Maxwellian). Then we can assume a source of known form (exponential in $-\text{energy}/T_c$) but unknown amplitude on the separatrix; the distribution function can now be expressed in terms of exponential integrals. The normalization is determined *a posteriori* by particle conservation.

In this paper we will present the idealized calculations described above; discuss the incorporation of physical effects, e.g., transition to a collisional solution at energies greater than a relativistic detuning energy, which lie outside the regime of validity of our assumptions; and compare the distribution function and integrated fluxes and densities obtained from our calculation with those obtained from the multi-region bounce-averaged Fokker-Planck code SMOKE.

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CALCULATION OF SELF-CONSISTENT POTENTIAL
WITH A MULTI-REGION FOKKER-PLANCK CODE*

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The multi-region bounce-averaged Fokker-Planck code (SMOKE) has been upgraded to solve for the self-consistent potentials in a magnetically confined plasma. The numerical procedure is to solve for quasi-neutrality at a number of cardinal points in the axial direction at the beginning of a time step and then calculate the distribution function at the new step. During the iteration for the potential we hold the distribution function fixed in (ϵ, μ) space for each region. It would be preferred to fix the distribution in (μ, J) space, but as yet this is not implemented. As an example, we use this code to study the electron distribution, with an analytic model for ions, in a thermal barrier configuration of a tandem mirror. Similarly, we solve for the ion distribution with a Maxwellian background of electrons. Results will be presented.

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AN EFFICIENT NUMERICAL SCHEME FOR 1-D SPECTRAL 2-D GRID POINT RESISTIVE MHD CODE*

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We have successfully implemented a new efficient semi-implicit time-advancement scheme in the 3-D resistive MHD initial value code RPD¹ for a square cross section tokamak. The key characteristics of this code are as follows:

- 1) Numerically advance the 3-D compressible full resistive MHD equations linearly or nonlinearly.
- 2) Fourier analyze dependent variables in the toroidal direction only. Use a finite difference representation in the two Cartesian directions of a constant toroidal angle plane.
- 3) Can handle nonsimply connected boundaries including poloidal divertor rings.

The new semi-implicit scheme is based on that by Harned and Kerner² and it removes the fast mode time step constraint. To circumvent the large matrix problem that results from a 2-D grid point representation, however, we have applied an operator splitting method to the anisotropic semi-implicit operator. As a result, only small tridiagonal matrices need be solved in advancing the fluid velocity. We have conducted exhaustive numerical tests in a divertorless geometry comparing the new scheme with our old scheme¹ that is mostly explicit. Typically, the new code runs faster than the old code by a factor of one to three times the aspect ratio. Grid convergence, step size convergence, linear growth rates of 2/1 and 1/1 resistive modes and saturated 2/1 island width were all found to be satisfactory. A version of the code with four divertor rings is being run to determine the effects of the proximity of the mode rational surface to the divertor separatrix and the plasma in the common flux region.

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Ballooning and interchange stability of plasmas with equilibrium flows

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Plasma flows of the order of the sound speed have been observed during neutral beam injection on PDX, ISX-B and more recently, TFTR. It is shown that equilibrium flows have striking effects on the MHD stability of ballooning and interchange modes in axisymmetric plasmas.

Equilibrium flows are represented as $\vec{v} = [\Phi(\Psi)/\rho]\vec{B} + R\Omega(\Psi)\hat{\phi}$, where $\Phi(\Psi)$ and $\Omega(\Psi)$ are arbitrary functions of Ψ , and (R, ϕ, Z) is the standard cylindrical coordinate system with ϕ as the direction of symmetry. From a WKB theory for $n \rightarrow \infty$ ballooning modes, it is shown that ballooning modes do not exist unless $\Omega(\Psi)$ is a constant (independent of Ψ). Sufficient conditions for stability, which extend earlier work [E. Hameiri and P. Laurence, J. Math. Phys. 25, 396 (1984)] are derived. In the case of rigid toroidal rotation, a possible stabilizing mechanism for ballooning modes on internal flux surfaces is provided by the centrifugal separation of constant-pressure and constant-density surfaces. Numerical results from the Lausanne code CLIO will be presented.

The ideal MHD stability of cylindrical equilibria with sheared poloidal and toroidal flows is investigated analytically and numerically. A generalization of the Suydam criterion is derived. Sheared flows below the propagation speed for the slow waves are found to be destabilizing, but the growth rates are small. Just above the propagation speed for the slow waves, the resonant surface is Suydam-stable, but the infinite sequence is captured by an unstable slow wave continuum. This phenomenon of exchange of instability is generic in the presence of equilibrium flows.

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SHERWOOD THEORY MEETING 1987

**Energy Conservation and Wave Tunneling
for Hermitian Differential Operators of Arbitrary Order***

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A variational formulation of the Vlasov-Maxwell equations gives rise to Hermitian differential operators of arbitrary high order.¹ Hermiticity arises when particle resonances are not present or neglected, e.g., for wave propagation perpendicular to a magnetic field. For such systems, the general problem of wave tunneling is examined and consistency with energy conservation is obtained. Exact energy conservation is a consequence of the Hermitian form of the operator, and the conserved energy flow can be related to the bilinear concomitant of the solution and its complex conjugate. It is shown that this bilinear form describes asymptotically the usual WKB energy flow and is additive with respect to the individual modes. Representative cases of wave tunneling are analyzed by WKB techniques that use analytic graphical methods which generalize the Furry rules. Reflection and transmission coefficients are thereby obtained. They properly account for phase change across tunneling regions, graphically determine the direction of energy flow of spatially disconnected roots, and energy conservation is obtained within the WKB framework.

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APPLICATIONS OF SYMBOLIC COMPUTING TO
COMPUTATIONAL PLASMA PHYSICS*

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Although much of computational plasma physics is traditionally oriented toward numerically intensive procedures, there are some areas where modern symbolic computing techniques may be applied to substantial advantage. Three specific examples are described. First, progress is reported on ANALYZ [1], a hybrid symbolic-numerical system which works in conjunction with typical scientific computations, e.g., eigenvalue problems, nonlinear optimization, to facilitate the conduct of parametric analyses. Second, the flexibility of LISP based programming is demonstrated by presenting a symbolic system which "reads" FORTRAN COMMENT lines describing the input and output parameters of an existing FORTRAN code, sets up a database for these quantities, and then automatically writes the FORTRAN subroutines necessary to interface the FORTRAN code to the LISP database system. Finally, in a more conventional vein, MACSYMA is used to derive the linear plasma response within the context of a magnetized fluid slab. Despite the relative brevity of the MACSYMA code, the linear response may be derived for a variety of interesting cases--homogeneous or inhomogeneous equilibrium, cold or warm fluid, cross-field or field-aligned drifts, electromagnetic or electrostatic polarizations, and with or without the geometric optics approximation.

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QUASILINEAR EVOLUTION OF BALLOONING MODES

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The quasilinear evolution of ballooning modes is analyzed from three points of view. A quasistatic resistive energy principle is presented for finite pressure toroidal systems with islands. The islands flatten the pressure gradient inside the separatrix, while the second derivative of the pressure is large near the separatrix. The satellite harmonics are strongly destabilized by p'' at the separatrix. Saturated island widths are calculated by setting the released free energy to zero. The quasilinear analysis of plasma stability gives a more pessimistic view of plasma stability.

Finite m effects are included and the most unstable modes occur when the resistive layer is comparable with the eigenfunction wavelength. A turbulent transport coefficient is calculated for saturated ballooning modes using finite m effects to determine the spectral cutoff.

An analytic treatment of the Rutherford regime of ballooning modes is presented. The principal result is that the threshold amplitude for a transition from linear stability to quasilinear instability occurs when the island width is comparable with the resistive layer. We find that the resistive interchange and the resistive twisting mode can destabilize the tearing ballooning mode.

Finally, a computational method for linear and quasilinear ballooning modes in physical space is presented. The general three dimensional MHD equations are developed in a Fourier series in flux coordinates. The equivalence of harmonics for high m modes is used to reduce the equations to a nonlocal operator on a single harmonic. In past attempts, the boundary condition of decay at infinity has caused severe numerical difficulties. These problems are avoided by using a mixed representation of finite elements and Laguerre polynomials.

REDUCED EQUATIONS TO DESCRIBE
THE INTERNAL KINK MODE IN TOKAMAKS

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In order to study the sawtooth phenomenon in tokamaks without neglecting pressure and toroidal curvature, reduced MHD equations must be expanded two orders higher in the inverse aspect ratio, $\epsilon = a/R$, than when only resistive effects are included. We have derived a set of reduced equations which includes the pressure driven mode in toroidal curvature through an expansion in ϵ . These equations are simpler than those previously derived.¹ When the density is taken to be a constant, only three scalar quantities must be evolved in time. These equations are being incorporated into our reduced MHD sawtooth simulation code. Results to date will be presented.

Work supported by U.S. Department of Energy.

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SHERWOOD THEORY MEETING 1987

**Plasma Current Sustained by the Burning $D - {}^3\text{He}$ Fuel
in a Field Reversed Configuration****Toshi Tajima, H. L. Berk, and H. Momota*Institute for Fusion Studies
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We consider an advanced fuel burning $D - {}^3\text{He}$ plasma in a field reversed configuration and study the effect of the charged fusion products on the equilibrium and the effect of synchrotron radiation on the power output. The field reversed configuration has at least two significant positive characteristics for a burning advanced fuel: (i) a potential for a high plasma beta with lack of the toroidal field; (ii) favorable geometry for direct energy conversion of charged fusion products. It can be shown that because of the radiative energy losses due to synchrotron and Bremsstrahlung radiation for advanced fuels a number of necessary physical conditions arise for a reactor. At the same time, a number of new operational options arise because of the predominant fusion energy in charged particles and the low neutron fluence.

The physics issue we have identified thus far is the nature of the current supported by the charged fusion products. We focus primarily on the nature of the fusion product current carriers by studying the distribution of charged fusion particles in the FRC by analytical and numerical methods. A fraction of the charged fusion products escapes directly, while the others are trapped to form a directed particle flow parallel to the plasma current. The resultant current density produced by these particles can be comparable to background plasma current that produces the original field reversed configuration in a $D - {}^3\text{He}$ reactor. Self-consistent equilibria arising from the currents of the background plasma and fusion protons are constructed where the Larmor radius of the fusion protons is of arbitrary size. Various reactor relevant parameters, such as the synchrotron radiation power, are examined. As synchrotron radiation power loss can be comparable to fusion power, it is vital to have a self-consistent equilibrium profile to take into account the absorption and emission. We present a relatively simple model that accounts for complex spatial dependence. Without wall reflection synchrotron losses and fusion production are comparable for a pressure profile where $\partial p / \partial \psi$ is constant, where p is pressure and ψ the magnetic flux. Only a relatively steep pressure profile or high reflectivity of the wall can reduce the synchrotron loss mechanism to say 20% of the fusion power produced by a $D^3\text{He}$ fuel.

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Computation of the Parallel Viscosity For
Transport Purposes In Stellarators

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Abstract

The final goal of this research is the self-consistent computation of interesting "observables" such as transport fluxes, parallel flows, Pfirsch-Schluter and bootstrap currents and the ambipolar electric field, in the low collision frequency regimes in stellarators. We attack the problem numerically and utilize ideas employed in a bounce-averaged transport study done by Mynick and Hitchon^{1,2} and concepts based on the moment formalism developed by Hirshman.³ The moment approach points out the importance of the "parallel viscous force density" $\langle \mathbf{B} \cdot \nabla \pi \rangle$ in that it is the quantity that gives rise to the bootstrap current and the so-called "axisymmetric flux". In order to find $\langle \mathbf{B} \cdot \nabla \pi \rangle$, two important requirements must be satisfied: the collision operator must be momentum conserving and the distribution function must be allowed to vary along a field line. The first point necessitates adjustment of the collision operator in the code of Refs. 1 and 2. The second remark requires interpretation. The bounce-averaged output $\bar{f}$ of the Mynick-Hitchon treatment is averaged over the helical ripples, but not over the "tokamak-like" variation of the B-field. Hence this $\bar{f}$ does contain important parts of $\langle \mathbf{B} \cdot \nabla \pi \rangle$, if not all of them (given that $\bar{f}$ is momentum conserving). The direct contribution to the viscosity of the ripple trapped particles (and the helical ripple induced perturbation on the "tokamak-like" blocked particles) is evidently not included. Its importance is expected to be small, but examination of this issue is asked for. Here, we intend to present the results of $\langle \mathbf{B} \cdot \nabla \pi \rangle$ due to $\bar{f}$ alone.

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LINEAR KINETIC SIMULATION OF THE N=1 TILT INSTABILITY IN THE FRC*

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We use the linearized hybrid particle code FLARE to simulate the kinetic evolution of the $n=1$ tilt mode in the FRC. An initial-value approach is used to integrate the linearized Vlasov equation for the ion species, by using integration along unperturbed orbits. The electrons are treated as a fluid. We will present results on the growth rate of the tilt mode for various values of the ion gyroradius. These results will be compared to results obtained with a complimentary approach involving the use of the dispersion functional formulation of the Vlasov fluid model.

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A Nonlinear Mechanism for Drift Wave Induced Particle Transport*

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A recent study of drift instabilities in a shear-free slab using gyrokinetic particle simulation has shown that, in a system dominated by a few low- k modes with $\Delta\omega/\omega \lesssim 1$, the steady state particle flux, which is intrinsically ambipolar, increases drastically with electron-ion collisions.¹ A closer examination of the simulation results has revealed that the enhancement of the particle flux is accompanied by an increase in guiding center density for both species near the vicinity of the maxima of the electrostatic potential--a phenomenon which suggests particle trapping. Moreover, the regions of increased guiding center density become more pronounced as the simulation progresses. [Note that, in the gyrokinetic jargon, the ion density is composed of two components: the guiding center density and the polarization density.¹ The former is described by the equations of motion, whereas the latter appears in the gyrokinetic Poisson equation.] As a starting point for the understanding of the mechanisms involved, we have studied the ion motion in a time-varying potential field modelled after the simulation, where the parallel motion of the ions can be ignored. It is found that the formation and the growth of the regions of enhanced ion guiding center density are the results of convection of the ions that are trapped by the saturated drift waves, which, in turn, have a net phase velocity directed down the density gradient. The origin of this net phase velocity, which may involve the $\mathbf{E} \times \mathbf{B}$ nonlinearities and the electron velocity space nonlinearity, has yet to be resolved. The entropy balance equation derived from the governing equations is in agreement with the simulation results, which indicate that the growth of the enhanced density regions produces an entropy decrease which balances the particle flux.

*Work supported by U. S. D. o. E. Contract No. DE-AC02-76-CHO-3073.

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SUBGRID SCALE CLOSURES FOR MHD: Renormalized Transport Coefficients

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Turbulence usually results in the excitation of small scales, which can not be adequately treated by present-day or near-future supercomputers. Here we critically examine the renormalization group procedures used in Navier-Stokes turbulence¹⁻⁴ to model away the small subgrid scales. Typically^{1,2} only an infinitesimal mode band is eliminated, resulting in a renormalized viscosity and coupling coefficients. On the other hand^{3,4}, successive mode band elimination leads also to higher order nonlinearities which do effect the renormalized coefficients.

We apply these procedures to MHD and Alfven turbulence, for both forced and free decay, and calculate the renormalized eddy viscosity and magnetic diffusivity.

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STEADY-STATE RFP COMPUTATIONS

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Earlier initial-value pseudospectral computations^{1,2} for the reversed-field Z pinch are extended to the case of steady state operation. An externally-applied electric field increases linearly from zero to a constant value in 20 Alfven time units; it is applied to an initially current-free uniform-density magnetofluid. Steady-state reversed-field operation is achieved in about 80 Alfven time units. The run proceeds for > 200 units more, and will apparently maintain steady-state operation indefinitely. In a layer surrounding the central current column, the B_z field is negative and typically ten per cent of its magnitude in the center.

The MHD fields are in no sense time independent. Fluctuations about the averages of all fields and global integrals persist; as in some RFP measurements,³ these are typically at the 5 to 10 per cent level. The kinetic energy of the flow field is on the average about 6 per cent of the magnetic energy. The central region has $j \cdot B / jB$, but not $j \cdot B / B^2$, close to a constant value. Helical irregularities come and go, and occasionally resemble the "slinky" mode identified at General Atomic⁴. The dynamics are not much clarified by considerations of individual Fourier modes.

The computational conditions are: 16 x 16 x 64 resolution, time step 1/125 Alfven time. A time-independent variable resistivity profile is maintained, increasing toward the wall. The Lundquist number starts out at 200 on-axis and 50 at the wall, and occasionally increases to as much as 2000 on-axis. Free-slip boundary conditions are imposed at the (square) xy boundaries and everything is periodic in z, with an aspect ratio of 8. B_z starts out uniform and, maintaining constant total flux, eventually ranges from ten times its average value in the center to close to minus its average value near the wall.

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Numerical Simulation of Driven Drift-wave Turbulence*

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Density gradient-driven turbulence in a 2D sheared slab is studied numerically. Access to the free energy in the density gradient is provided by the dissipative trapped particle instability, or alternatively the fluctuations are driven by shear in the global $\mathbf{E} \times \mathbf{B}$ velocity profile. Separate equations for the density and potential fluctuations are advanced, allowing for departures from the Boltzmann relation near the resonant surface, where the parallel wavenumber vanishes. Shear damping by outward propagating sound waves serves to localise the fluctuations. Diagnostics include statistical moments and coherence lengths to measure intermittency and estimate diffusion coefficients, and $S(k, \omega)$ plots to indicate the strength of the turbulence. Saturated state amplitudes and properties are given as functions of the collisionality, which controls the width of the nonadiabatic layer. Nonlinear suppression of shear damping, seen previously in the quasi-adiabatic case,¹ is investigated as well.

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

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SHERWOOD THEORY MEETING 1987

**Toroidal Effects on Shear Alfvén Waves
Destabilized by Alpha Particles***

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It has been shown¹ that fusion product alpha particles can resonantly destabilize the shear Alfvén wave, both the global and the kinetic eigenmode versions thereof, by the wave-particle interaction associated with their parallel motion. The global Alfvén eigenmodes are very weakly damped by electron Landau damping and are therefore more strongly destabilized than the kinetic Alfvén eigenmodes. This instability is driven by the alpha particle density gradient. Previously, we found that, for the parameters of the proposed Compact Ignition Tokamak, the expected birth distribution of alpha particles is narrow enough to predict instability for the most strongly growing global Alfvén eigenmode, the $n = 0$, $m = -2$ mode.² These previous studies were done with the assumption of cylindrical geometry. Here, we investigate the effects of toroidicity on this problem. In a toroidal device, the basic cylindrical global Alfvén mode can become coupled to several sideband modes. Such coupling can introduce heavy collisional damping near the edge of the plasma and thus reduce the growth rate of the basic $(0, -2)$ cylindrical mode. Detailed numerical results that demonstrate this stabilizing effect of toroidicity will be presented.

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A HYBRID VLASOV-FLUID MODEL OF KINETIC IONS AND MASSLESS FLUID ELECTRONS*

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We have developed 2-D and 3-D computer models with kinetic ions and massless fluid electrons. We have also developed the analytic aspect of the linear theory of the model; we are able to eliminate the electric field from the analysis and obtain a Vlasov model involving only the ions and the perturbed B field. From this we obtain the linear dispersion relation for arbitrary angles of propagation. The model exhibits such important effects, such as ion Bernstein waves, ion cyclotron waves, low frequency whistler waves, Alfvén waves, and magnetosonic waves. The model shows excellent agreement with the analytic dispersion relation. The model has thus far been used to study the microinstabilities analogous to the ones which can arise in neutral beam heating of a plasma, i.e., the ion ring in velocity space instabilities. The growth rates of the various modes propagating at right angles to the external magnetic field have been measured and thus the most unstable modes have been found; nonlinear saturation effects are investigated.

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Steady States of the Kuramoto-Sivashinsky Equation*

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The Kuramoto-Sivashinsky equation is one of the simple nonlinear partial differential equations.

It is

$$v_t + 4v_{xxxx} + \alpha \left[v_{xx} + \frac{1}{2}v_x^2 - \frac{1}{4\pi} \int_0^{2\pi} v_x^2 dx \right] = 0 \quad ,$$

where the subscripts t and x denote the time derivative and the space derivative, respectively.

It represents many physical situations such as dissipative trapped ion modes in plasma, unstable flame fronts, and interface of two viscous fluids.

The fourth order spatial derivative term comes from dissipation, the second order spatial derivative term gives rise to instability, and the nonlinear term gives rise to mode coupling. The transport of energy through the nonlinear mode coupling produces a balance between long wave instability and short wave dissipation. The last term is introduced to keep the level of the solution constant; $\partial_t \int_0^{2\pi} v dx = 0$. The quantity α is the bifurcation parameter.

Bifurcations and stability of each stationary state are examined. The index rule is useful.

If all the stationary and periodic solutions are unstable for some α , one may expect chaotic behavior of the system for that α , since any orbit governed by the equation may have to wander around forever in the phase space. The orbits will then lie on strange attractors.

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"Free Electron Lasers"

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1-D TRANSPORT CALCULATIONS FOR Z-PINCH FIBERS

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1-D transport simulations are being conducted for Z-Pinch fibers in order to determine plasma performance for both the present experiment and a proposed experiment. Results indicate that as the current ramps from 100 KA to 1.1 MA the plasma rapidly moves to a state where the behavior of all dynamical variables (i.e. $n, T_e, T_i, V_r, B_\theta$) is time and space separable. The similarity variable is the radius normalized to the pinch radius, which contracts by almost a factor of 3. These solutions appear to be attractors in that these separable states are achieved even though they are not satisfied by the initial conditions.

The practical implications of this are that the plasma moves into a state where the functional dependence of the pressure profile in the moving coordinate system is time-independent. The shape of this profile, and perhaps the plasma stability properties, can then be controlled merely by the time dependence of the axial current. Simulations of the proposed experiment indicate the possibility of achieving $n\tau_E > 10^{14}$ with $T_i \sim 3 - 4$ KeV.

OSCILLATING FIELD CURRENT DRIVE FOR THE REVERSED-FIELD PINCH*

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Oscillating field current drive is examined with both a one-dimensional hyper-resistive model and a three-dimensional nonlinear resistive MHD code. Unlike simpler models which considered only the time-averaged currents due to the applied oscillating fields or assumed the plasma always to be in a relaxed state, both of these models treat the plasma response to the oscillatory fields. The three-dimensional model contains the full plasma dynamics while the one-dimensional model solves mean field equations with a hyper-resistive term derived from the time average over fluctuating fields due to the nonlinear interaction of tearing modes. Hyper-resistivity profiles for the one-dimensional model are computed from saturated tearing modes in the three-dimensional code. Both models are used to study present experimental parameters on the Los Alamos ZT-40M experiment. For the experimental parameters a strong dependence on frequency is found. The oscillation period used on ZT-40M is long compared to ideal MHD time scales and short compared to the resistive diffusion time. The computations indicate that for this oscillation period or for shorter periods a small amount of current drive is produced and the plasma remains reversed throughout the oscillations, as observed experimentally. For lower frequencies, however, it is found that the plasma can lose reversal and have violent oscillations which result in the current changing sign. The ZT-40M experiment operates with a steady-state field in addition to the oscillatory components. If this steady-state field is removed, so that there is no net volt-second consumption, acceptable parameters for current drive become much more difficult to achieve. This is due to the fact that if the plasma is allowed to fully relax (i.e., low frequency) the plasma will alternate between equilibrium states with the current pointing in opposite directions. Conversely, if the frequency is too high current drive becomes negligible. The simulations demonstrate that the dynamics of the plasma make the achievement of a pure current drive RFP much more difficult than it would appear from simpler models which considered only the time-averaged part of the induced current. For a reactor relevant experiment the computations show that the choice of frequency will be critical in order to maintain a sufficient amount of current without net consumption of volt-seconds and to avoid an unacceptably violent plasma response.

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Determining the Coils for Stellarators

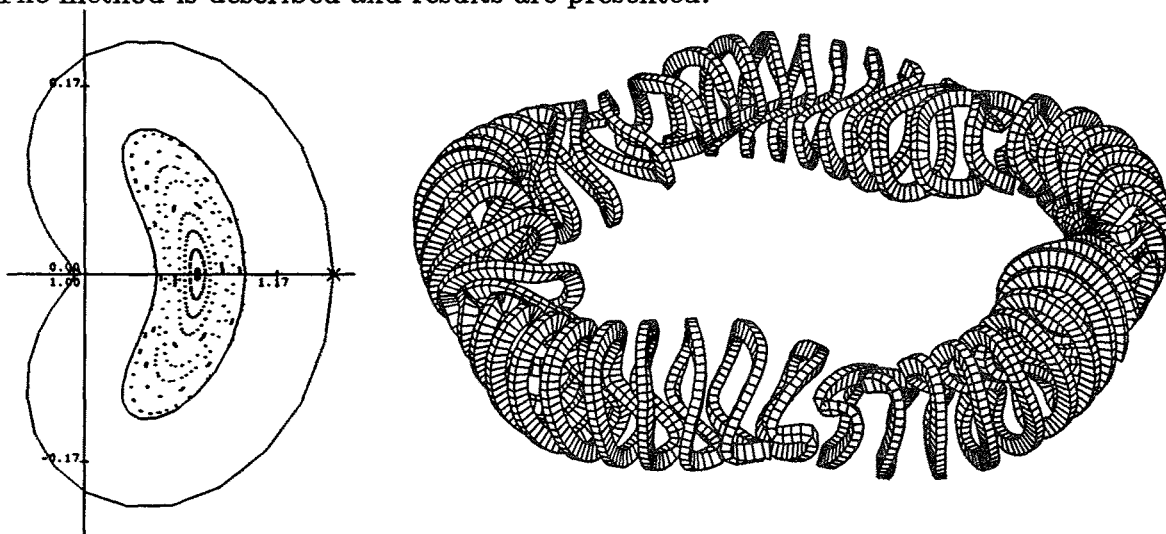
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In stellarator research it has proved useful to separate the discussion of the magnetic properties of a configuration from its realization by coils. The magnetic properties are completely determined by the geometry of an outer magnetic surface close to the ergodic region outside the confinement region. Optimizing the magnetic properties of stellarators by optimizing the shape of the outermost flux surface (see, for example, [1]) then results in the problem of finding coils which reproduce this flux surface. The following method was developed to solve this Neumann boundary value problem. On a closed surface surrounding the plasma region a surface current is determined such that the normal component of the magnetic field $\vec{B}$ produced is minimized on the plasma boundary: $\vec{B} \cdot \vec{n} = 0$ ($\vec{n}$ = normal to the boundary). The surface current, whose current lines are poloidally closed, is then discretized into a finite number of coils [2].

In a second step the outer current-carrying surface is optimized to realize desirable properties of the coils, e.g. (minimal and maximal) distance to the plasma boundary and minimal curvature.

Figure 1 shows a Poincaré plot of a Helias-type vacuum field $\vec{B}$, where $\vec{B}$ is generated by 10 coils per period on the outer surface. Among the magnetic characteristics are $\iota_0 = 0.78$, $\iota_E \approx 1$, a magnetic well of about 0.01. The modular coils are shown in Fig. 2. The method is described and results are presented.



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Free-boundary Helias Stellarator Equilibria

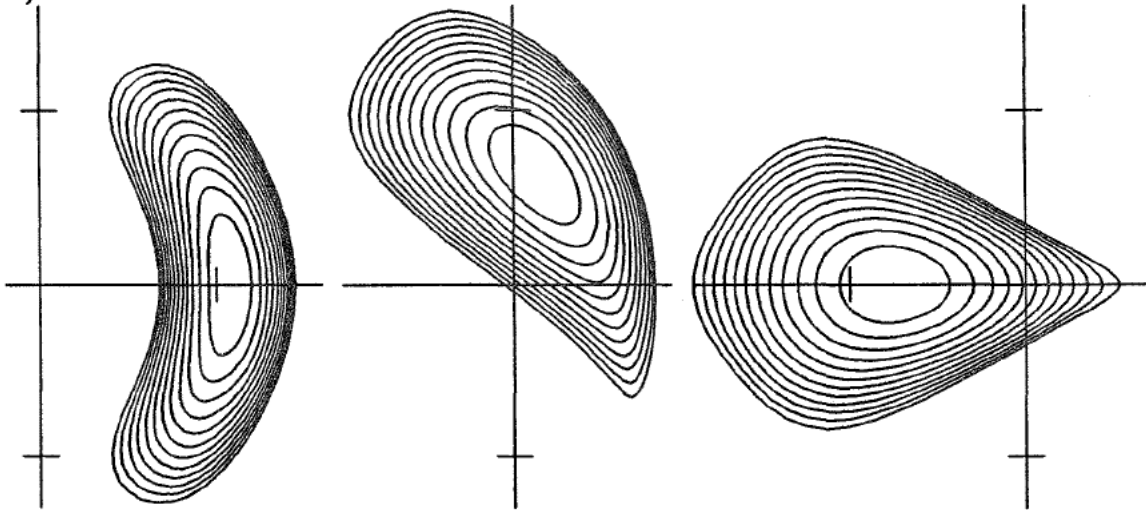
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The NEMEC three-dimensional free-boundary MHD equilibrium code [1] is applied to the Helias stellarator configuration [2]. The former parameter studies of the Helias class of stellarators, based on the computation of three-dimensional fixed-boundary equilibria which are stable according to the resistive interchange criterion, yielded $\langle\beta\rangle$ values of up to 0.09.

A method has been developed to construct external currents producing the Helias vacuum field [3, 4] so that the NEMEC free-boundary code can be applied to the Helias configuration.

Preliminary results show a beta-dependent outward shift of $\frac{\Delta R}{R} \approx 0.13\langle\beta\rangle$. The outward shift can be compensated with a vertical magnetic field $B_z/B_0 \approx 0.2\langle\beta\rangle$ (B_0 toroidal field).



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SOME NONLINEAR ASPECTS OF INTENSE PULSED ECRH*

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An experiment has been proposed by Livermore and M.I.T. to use the ETA-II Free-Electron-Laser (FEL) as an ECRH source for the Alcator C tokamak experiment to be moved from M.I.T. Intense pulsed ECRH offers the possibility of efficient plasma heating and current drive. The proposed experiment will have short pulses (5×10^{-8} sec) with a peak power of $4-8 \times 10^9$ Watts and average power $1-2 \times 10^6$ Watts. The peak electric fields in the plasma will be 10^5 to 10^6 Volts/cm. At these intensities nonlinear effects are more important than linear thermal effects in determining the absorption of the microwaves. Relativistic mass and trapping effects become important and novel schemes for current drive are possible. Parametric effects must be considered also, e.g. stimulated backscattering and parametric decay. With a second FEL source at lower frequency and lower power (perhaps a factor of 10), beat-wave acceleration of an electron tail can lead to a current-drive source with good efficiency.

We have examined nonlinear absorption analytically and with both Monte Carlo and self-consistent 2-D electromagnetic particle simulation codes. As the wave intensity increases the effective opacity decreases. The observed scaling of the absorption in the simulations agrees excellently with the theory. Parametric instabilities for ordinary waves resonant with fundamental cyclotron resonance on axis and for extraordinary waves resonant at the second harmonic have been surveyed. Backscatter by electrostatic ion cyclotron waves poses the biggest threat to wave penetration. Parametric decay processes that would lead to nonlinear absorption could occur for the extraordinary wave. However, bandwidth effects introduced by scattering due to edge fluctuations significantly inhibit convective parametric instabilities like backscatter. With a second pump wave chosen to produce a suitable beat wave with the primary ECRH wave, momentum can be efficiently deposited in an electron tail and current can be driven. Analysis and particle simulation of these effects will be reviewed.

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**In collaboration with W.M. Nevins, M. Porkolab, T.D. Rognlien, A.B. Langdon and B.G. Logan.

Ion-Electron Energy Transfer Near the Separatrix in Diverted Tokamaks*

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A new mechanism for energy transfer between ions and electrons in diverted tokamaks near the separatrix has been found. When ions are lost from a region approximately an ion banana width inside the separatrix by collisional scattering into loss regions in velocity space, a negative radial electric field must be present, since electrons cannot escape in this manner from as far inside the separatrix. When ions and electrons diffuse through the electric field in this region, the ions do work against the field, which does work on the electrons, so that thermal energy is transferred from ions to electrons. Electron anomalous diffusion and heat conduction are assumed to be present but the intrinsic (nonambipolar) electron loss rate is assumed to be smaller than the ion loss rate due to velocity loss region scattering. By starting with the exact energy and momentum equations for electrons and ions, an energy transfer term is found which is proportional to the radial electric field, and is specifically due to the ion loss region scattering. (This is in addition to the neoclassical energy transfer terms, in which the radial electric field cancels.) Near the separatrix, this term can be much larger than the classical collisional energy transfer term, proportional to the difference between the ion and electron temperatures. The possibility of this mechanism playing a role in the H-mode will be discussed.

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Scaling Law for Energy Confinement in
Turbulent Fluid Plasmas*

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ABSTRACT

Scaling laws for energy confinement in a turbulent plasma dominated by resistive interchange modes are revisited. Previous results, derived by renormalization techniques¹ as well as by invariant properties of the equations², are found to be inaccurate. The errors are due to improper approximations used in simplifying the governing equations.

Our analysis is based on a consistent low- β approximation, applied to both tokamaks and RFP's. The results are somewhat more pessimistic than in the earlier works. In particular, the energy diffusion coefficient, due to the collisionless flow of electrons₋₁ along stochastic magnetic field lines, is larger by a factor of β in the RFP case, and by a factor of $\epsilon/(\beta q^2)$ for a tokamak with inverse-aspect-ratio ϵ . Significantly, the RFP still yields higher temperature and β , and better confinement time, than a tokamak with a similar magnetic field strength².

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"Resistive Instabilities in Toroidal Confinement"

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"Strong Plasma Turbulence"

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"Universal and Not So Universal Instabilities"

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BOOTSTRAP CURRENT IN NONAXISYMMETRIC TOROIDAL PLASMAS*

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An analytic expression for the bootstrap current in nonaxisymmetric toroidal plasmas has been given by Shaing and Callen [K. C. Shaing and J. D. Callen, *Phys. Fluids* **26**, (1983) 3315]. This expression contains a number of line integrals that are difficult to evaluate numerically; consequently, it is desirable to devise a formula that is easier to use. Such a formula was recently presented [K. C. Shaing, S. P. Hirshman, and J. S. Tolliver, *Phys. Fluids* **29**, (1986) 2548], but requires a correction that is presented here. We evaluate the corrected formula for ATF-like stellarator/torsatron configurations and compare the results with those obtained using a numerical solution of the Fokker-Planck equation [S. P. Hirshman, K. C. Shaing, W. I. van Rij, C. O. Beasley, Jr., and E. C. Crume, Jr., *Phys. Fluids* **29**, (1986) 2951], and those obtained in a recent numerical evaluation [T. Ohkawa and M. S. Chu, GA-A18688 (1986)] of the original analytic expression. Very good agreement among the results is obtained, demonstrating that the corrected formula is equivalent to the original analytic expression. We also compare results from the corrected formula and the numerical solution for a systematic variation of the helical and toroidal geometrical parameters and find agreement to within the accuracy of the numerical method.

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ECH-Driven Potentials in a Tokamak*

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If electron-cyclotron heating (ECH) is applied in a finite-aspect-ratio tokamak with sufficient strength to drive a significant non-isotropy in the electron distribution function, potential variation along a field line is required to maintain charge neutrality. The effect is strongest if the heating is applied in pulses short compared to ion-transit times and the collision times of hot electrons and ions, as in the proposed MTX free-electron-laser (FEL) heated tokamak. We evaluate the potential variation $\Delta\Phi$ for a hot-electron distribution function which is assumed to be a bi-Maxwellian at the ECH resonance zone. $\Delta\Phi$ is calculated for, and found to be successively smaller on, the hot-electron-transit, ion-transit, and ion-collision time scales. (The latter calculation is the one relevant to continuously applied ECH.) Taking parameters appropriate for initial application of the FEL to an ohmically heated ($T_e \cong 1$ keV) discharge in MTX, it is found that $\Delta\Phi \sim 0.3T_e$ on the hot-electron-transit time scale, dropping to about $0.2T_e$ on the ion-transit time scale, and then decaying on the hot-electron collisional time scale, which is comparable to the pulse repetition period; the coefficients are about doubled for $T_e = 4$ keV. The potential has both poloidal and toroidal variation. Possible consequences include enhanced neoclassical transport, ion heating, and drive for instabilities.

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Abstract Submitted for the
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San Diego, California

Category: Plasma Equilibrium and Stability

Optimal Shaped Cross-Section for Tokamaks Against External Kink Modes. S. P. Hakkarainen, J. P. Freidberg, Plasma Fusion Center, M.I.T. — We investigate the MHD-stability of a tokamak with an arbitrary aspect ratio against external kink modes using the sharp boundary (skin current) model with conducting walls at infinity. The magnetic potential problem is solved using a Green's function at the plasma surface. Explicit expressions are calculated for the general compressible $n = 0$ mode, as well as the incompressible $n = 1$ and $n = 2$ modes. The plasma surface is parametrised in a poloidal angle-like variable. The horizontal direction, $R - R_0$, is given as a Fourier series of this variable and the vertical direction, Z , as a simple function of the same variable. The optimisation is performed over the Fourier coefficients leading to the cross-section with the maximum stable β against external kink modes. Results and reasons are given as functions of machine size, which is defined in terms of the "aspect ratio" of a rectangular vacuum chamber enclosing the plasma. In the context of kink modes, some issues concerning q_ψ and q_* are also discussed.

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Category: Plasma Equilibrium and Stability

Stability Properties of Tokamaks with a Resistive Wall. S. W. Haney, J. P. Freidberg, Plasma Fusion Center, M.I.T.*— A variational principle, based on the Extended Energy Principle, is derived to describe the stability of arbitrary three dimensional external modes in an arbitrary three dimensional plasma configuration with a thin resistive wall. These modes can be stabilized by a close-fitting perfectly conducting wall, but are always unstable in the presence of a resistive wall. A simple, analytic formula estimating the resulting growth rates, which are comparable to the resistive diffusion time through the wall, is calculated using trial functions for the vacuum fields. This estimate is seen to depend on the properties of the ideal system with and without a perfectly conducting wall located at the same position as the resistive wall. As an application of this theory, the stability of shaped tokamaks against rigid axisymmetric ($n = 0$) modes will be considered.

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SHERWOOD THEORY MEETING 1987

Anomalous Electron Energy Transport in Tokamaks **S. M. Mahajan, Y. Z. Zhang, and H. L. Berk*

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A universal mechanism for anomalous electron energy transport in tokamaks with ohmic and/or auxiliary heating is proposed. It is suggested that the enhanced transport is caused by a low-frequency microturbulence induced by electron temperature gradients. Within the framework of nonlinear drift-kinetic-ampere equations, a renormalized strong turbulence theory is developed, and is manipulated to obtain the anomalous energy transport coefficient $D_{\perp}^T$, which is then used to solve the 1-D electron energy transport equation in cylindrical geometry. The solution of electron temperature profile shows that the energy transport effectively decouples from the particle transport implying that our model is consistent with the "principle of profile consistency." We also derive a formula for the characteristic central electron temperature and find it in good agreement with the available tokamak experimental data (ranging from 0.3 keV to 7.4 keV including the supershot in TFTR and monster mode in JET). Various scalings contained in the temperature formula are compared with experiments, and the known empirical scalings. Parametric dependence of the electron energy confinement time $\tau_{E_e}(0)$ is also derived, its nonlinear dependence on $n_e(0)$ is in a good agreement with the well-known Alcator-A experimental results.

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CROSS-SPECIES COLLISIONAL VISCOSITY*

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The viscosity tensor due to unlike particle collisions in a magnetized plasma is calculated by allowing for finite relative flow ($|\mathbf{V}_{ab}| \equiv |\mathbf{V}_a - \mathbf{V}_b| \sim v_{th}$) and finite mass-ratio ($\frac{m_a}{m_b} \sim 1$). The calculation is based upon a previously developed moment approach¹. In this formalism, the collisional tensor moment

$$C_{ab} \equiv \int d\mathbf{v} m_a (\mathbf{v} - \mathbf{V}_a) (\mathbf{v} - \mathbf{V}_a) C_{ab}(f_a, f_b)$$

is evaluated by assuming the lowest order distribution functions to be moving Maxwellians $f_{M_a}(\mathbf{v} - \mathbf{V}_a)$, $f_{M_b}(\mathbf{v} - \mathbf{V}_b)$. One significant result of this calculation is the toroidal momentum transport due to a rotating impurity species in neutral beam injection experiments. It is found that when $\frac{|\mathbf{V}_{iI}|}{v_{th}} \sim 1$, the ion-impurity collisions will result in a viscous drag frequency $\nu_d \sim \delta \nu_{iI}$, which is δ^{-1} time larger than the usual Braginskii's collisional viscous drag when $\frac{n_I Z_I^2}{n_i Z_i^2} \sim 1$. Here $\nu_{iI} = \frac{n_I Z_I^2}{n_i Z_i^2} \nu_{ii}$ is the ion-impurity collision frequency and $\delta \equiv \frac{\rho}{L}$ is a small parameter corresponding to the ion gyroradius.

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IDEAL MERCIER STABILITY IN 3-DIMENSIONS*

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A 3-D evaluation of Mercier criterion^{1,2} has been added to the equilibrium code VMEC developed at ORNL.³ The Mercier criterion for stability for a full 3-D geometry can be written as:

$$D_S + D_W + D_I + D_{P-S} > 0 .$$

Here the four terms are the shear, magnetic well, net current and Pfirsch-Schlüter current contributions respectively. To evaluate the Mercier criterion, we have used as input the VMEC equilibrium results and detailed convergence studies have been performed. The 3-D equilibrium and Mercier criterion will be presented for Heliotron-E, ATF and the M=3 configurations being studied as reference designs for the Australian Helic H-1. The dominant contributions in the Mercier criterion arise from different terms for the different configurations. For Heliotron-E, the dominant stabilizing contribution comes from the shear, while for the ATF, the combination of the well and the shear are stabilizing. For Helic configurations only the well, and the Pfirsch-Schlüter terms are important. For the Helic configurations studied the last term was the dominant one, and large destabilizing contributions arise near the low order resonant surfaces.

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Nonlinear Absorbtion and Current Drive with Intense Microwave Pulses*

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Free electron lasers (FEL's) in the electron cyclotron frequency range have been proposed as an efficient means of heating and driving current in tokamak plasmas¹. The proposed FEL will have short pulses ($\delta t \approx 5 \times 10^{-8}$ sec) with a peak power of 4—8 GW. The RF electric field in the plasma will be in the range 10^5 — 10^6 V/cm. At these high intensities, nonlinear modifications of particle orbits are important in the absorption of microwave power². These nonlinear orbit modifications also effect the RF current-drive efficiency. In general, a high current drive efficiency can be achieved if the intense microwave pulses can be made to efficiently produce high energy passing electrons with the correct sign of parallel velocity. Several schemes for using the microwave pulse directly to produce such high energy electrons are investigated using a Hamiltonian formulation of the equations of motion in the presence of the wave. These schemes are also investigated numerically using Monté Carlo and particle simulation codes.

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

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A New Cellular Model For Magnetohydrodynamics
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ABSTRACT

A Cellular Automaton (CA) is a discrete dynamical system consisting of a set of cells on a lattice, a definition of the state of the system in terms of one or more integer quantities defined at each cell, and a set of local rules for simultaneously updating the state of all the cells. With properly chosen microscopic rules and a suitably defined correspondence between microscopic and macroscopic quantities, one can design CA models that obey differential equations of physical interest such as hydrodynamics¹ and magnetohydrodynamics (MHD)². It has been suggested that the numerical simulations based on CAs may have advantages over those based on classical methods. Here we introduce a new type of two dimensional cellular automaton method for computation of fluid systems such as magnetohydrodynamics that involve transport of more than one vector field. Particle population on the hexagonal lattice is described by a 36-component tensor referred to a hexagonal lattice. By appropriate choice of the coefficients that control the modified streaming algorithm and the definition of the macroscopic fields it is possible to compute both Lorentz force and magnetic induction effects entirely locally.

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Energetic particle stabilization of ballooning modes in a tokamak of finite aspect ratio

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It has been suggested [M.N. Rosenbluth, S.T. Tsai, J.W. Van Dam and M.G. Enquist, Phys. Rev. Lett. 51, 1967 (1983)] that the introduction of highly energetic trapped particles in the bad-curvature region of a tokamak may allow direct stable access to the second regime of stability. This theory is revisited, allowing for both non-drift-reversed ($\omega_{*h} \bar{\omega}_{dh} > 0$) and drift-reversed ($\omega_{*h} \bar{\omega}_{dh} < 0$) particles. When $\omega_{*h} \bar{\omega}_{dh} > 0$, the theory gives a sufficient condition for stability. However, when $\omega_{*h} \bar{\omega}_{dh} < 0$, for which the theory gives a sufficient condition for instability, an additional region of ballooning instability is found. This region of instability is akin to that which causes the Van Dam - Lee - Nelson limit in the EBT, and imposes operational constraints on the proposed scheme for stable access to the second regime.

The effects of finite aspect ratio are included in analytic equilibria which are computed from the Grad-Shafranov equation with anisotropic pressure by means of an expansion in the inverse aspect ratio. The ballooning stability of these equilibria are determined numerically and depend sensitively on the aspect ratio. Comparative studies are given for tokamaks of different aspect ratios. Finally, an experimental scenario is described for implementing the transition scheme using hot electrons in the Second Regime Experiment (SRX) proposed at Columbia University.

GLOBAL ICRF MODELING IN LARGE NON-CIRCULAR TOKAMAK PLASMAS WITH FINITE TEMPERATURE*

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Full wave ICRF coupling calculations¹ in two and three dimensions have been extended to treat tokamaks with non-circular flux surfaces and conducting boundaries. The magnetic field configuration is derived from a Solov'ev equilibrium² with finite radial and poloidal magnetic fields. The conducting boundary may be of arbitrary shape. The mode conversion model is that of Colestock et al.³ in which the fourth order finite temperature wave equation is reduced to a second order equation which describes the effects of mode conversion on the fast wave but neglects the detailed structure of the ion Bernstein wave. Results show the effect of non-circular cross section on excitation, wave propagation, and absorption in Doublet III-D and JET. Also, in the limit of circular cross section, toroidal phasing of the resonant double loop antenna design for TFTR is studied.

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A KINETIC FRC MODEL

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Kinetic effects may play an important role in determining the stability and perhaps confinement properties of a Field Reversed Configuration (FRC). In cylindrical geometry, we have found collisionless equilibrium distribution functions ($f_{s0}(H, p_\theta)$) that yield macroscopic equilibrium profiles that may model well the profiles of a long, nearly collisionless FRC. Unlike previous kinetic models of the FRC, these distribution functions allow for non-isothermal, diamagnetic ions and finite temperature electrons. The model allows quick computation of the equilibrium state, making practical the study of kinetic effects upon the evolution of the equilibrium due to transport. An algorithm for computing the equilibrium state is discussed. Sample equilibria are presented. We show that in the guiding center limit these distribution functions are the highest entropy solutions of the Vlasov equations consistent with given macroscopic moments (eg. n_i, T_i) and fields. Finally, we present the state of development of a transport model that solves for the slow-time evolution of f_{s0} due to both turbulent and collisional transport (including non-local ion effects).

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THEORY OF TRAPPED-PARTICLE-INDUCED RESISTIVE FLUID TURBULENCE

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Recent years have seen a substantial amount of theoretical effort invested in pursuit of possible mechanisms which can explain the experimentally-observed anomalies in the transport of heat. One focus of this search has been resistive pressure-gradient-driven turbulence, which naturally evolves from the robust linear resistive interchange-ballooning family of instabilities, and which has been proposed as a leading candidate for anomalous transport in tokamaks¹, RFP's², and stellarators³. These theories have been predicated on the collisional MHD approximation, so that their applicability is limited to the low-temperature, edge regions in present-generation experimental devices. A number of recent theories have sought to explore the plateau and banana collisionality regimes, and found that in this limit resistive interchange-ballooning modes would also be excited. It is the purpose of this paper to consider the implication of trapped-particle-induced resistive interchange modes⁴ for turbulence and anomalous transport.

For analytical tractability, the plasma is divided into a warm core component which is treated using resistive MHD theory, and an energetic trapped-particle component, which is treated using drift-kinetic formalism. The analysis proceeds from a set of three coupled equations relating the vorticity, the core pressure, and the trapped-particle pressure, while retaining the advective $\mathbf{E} \times \mathbf{B}$ nonlinearity in all three. This coupled set of equations is then analyzed by renormalizing the nonlinearities through iterative substitution techniques *à la* the Direct Interaction Approximation, where the nonlinear evolution of a "test" trapped-particle-induced mode is tracked through a background of multiple-helicity turbulence. Saturation conditions as well as estimates of the anomalous electron thermal conductivity for both the non-resonant "fluid" ($|\omega| \gg \bar{\omega}_{dm}$, where $\bar{\omega}_{dm}$ is the bounce-averaged magnetic precessional drift frequency) and resonant ($|\omega| \sim \bar{\omega}_{dm}$) cases will be presented. The theory is expected to be relevant for moderate electron-temperature, high ion-temperature, collisionless plasmas, and as such, complements the resistive ballooning turbulence theory¹ which is more relevant for low-temperature, collisional plasma conditions, such as those that may exist near the edge region in large tokamaks.

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Transition to the Second Region of MHD Stability in a Large Aspect Ratio Tokamak

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Transport and stability calculations are presented for a large aspect ratio ($A = 9$), circular cross section tokamak experiment intended to explore the predicted second region of MHD stability. Evolving equilibria have been generated using a version of the BALDUR¹ transport code where the magnetic geometry changes consistently with the heat and mass diffusion. An interface between this code and various MHD codes permits both high and low n stability analysis of these equilibria. It is shown that neutral beam driven current programming can maintain q above unity on axis and modifies the shear profile in a manner that reduces both the radial extent of the high n unstable zone which develops and the time required to cross it. These calculations show transition to high n ballooning stability when $\epsilon\beta_0 = 1$. The transition, which is characterized by regions of low shear, has also been examined for low n stability.

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Quantum analysis of states near a separatrix*

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In classical systems, chaotic motion occurs first near the separatrix. Melnikov's proof shows that invariant surfaces near a separatrix are lost in the presence of a generic small perturbation. The mitigation of the onset of chaos by quantum effects has been shown to occur in the Standard Map and in the ionization of Rydberg atoms in high quantum states. Thus, we are motivated to determine how quantum effects modify the separatrix.

Our analysis shows that quantum effects strongly modify separatrix dynamics because the singularity near the classical separatrix is very weak (logarithmic). In particular, the classical excitation frequency, the orbit frequency, vanishes near the separatrix. The quantum excitation frequency does not, because there are no degeneracies in a one-dimensional quantum system. The minimum excitation frequency does approach zero in the semiclassical limit, but only with the logarithm of N , the number of quantum states in the system. As a result these effects should be observable in macroscopic systems.

The importance for fusion lies in the extremely collisionless regime in asymmetric toroidal systems. In this regime, there is residual transport due to chaotic motion. The diffusion rate can be calculated on the basis of separatrix crossing theory. Diffusion occurs because the classical adiabatic invariant breaks down near the separatrix. In contrast, the quantum adiabatic invariant need not break down, because the quantum excitation frequency does not vanish. Hence, quantum effects can restore the adiabatic invariant.

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MHD STUDIES OF THE INTERNAL TILTING MODE IN A
FIELD-REVERSED CONFIGURATION (FRC)*

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The internal tilting mode (ITM) is not observed in present large-gyroradius (compared to system size) FRC experiments. It has been shown¹ that at sufficiently small ion gyroradius the ITM may become strongly unstable with linear growth rate approaching ideal MHD predictions. Transition to instability will be observable only through nonlinear consequences of the mode, since linearly there is no effect external to the separatrix.

The ITM is studied using a 3-D, semi-implicit, resistive MHD code (FRC3D).² Finite differences in r and z and a Fourier representation in θ accurately represent the FRC. The current FRC3D has a fixed boundary and no thermal transport. Following previous work,³ a numerically obtained equilibrium and approximate linear mode are used as initial conditions. A linear growth phase with a growth time of $4.8\mu s$ (in excellent agreement with that obtained earlier⁴) is followed until the mode grows to a large amplitude. Nonlinearly, no evidence of saturation occurs. Rather the tilt grows until field-line tracing shows that reconnection has occurred.

Experimentally FRC's are observed to rotate, and the rotational velocity is thought to be determined by the density gradient scale length at the separatrix. Previous analysis^{5,6} has shown that for sufficient elongations this rotation may stabilize the ITM. The model is currently being extended to include rotation, and will be used to determine its effect on the nonlinear growth of the instability as well as the stability boundary.

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The Bifurcated Helical Equilibria*

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The lowest energy state of helical symmetry during the current flat-top is derived in the cylindrical limit by generalizing the previous work on the minimum energy state of axisymmetric plasmas.¹ The force free equilibria can be described by $[(1/r)(\partial/\partial r)(\partial\psi_p/\partial r)] + [(1/r^2)(\partial^2\psi_p/\partial u^2)] = -j_z = -C_F \exp(\psi_p/\lambda)$, where ψ_p is the poloidal flux and $u = \theta - kz$ is the helical variable. The helical equilibrium is shown to have higher energy content than its bifurcated counterpart with axisymmetry. The helical state can then be supported only when heating is effective. A conversion from the helical state to the axisymmetric state may therefore occur when heating becomes ineffective. The mechanism bears similarities to the marginal stability of helical equilibria with reflectional symmetry,² and the ideal half-coalescence instability of a (1.1) magnetic island.³ Implication for sawtooth crash and a single saturated island will be discussed.

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SEPARATRIX EFFECTS ON KINETIC ELECTROMAGNETIC TOROIDAL EIGENMODES*

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In the case of H-mode NBI-heated divertor plasmas, it is necessary to establish the proper behavior of the microinstabilities invoked under such conditions, specifically, the nature of the instabilities in the very steep gradient region near the plasma edge just inside the separatrix. In order to be consistent with the thermal fluxes calculated for the interior, the local thermal diffusivity in the edge zone must be greatly reduced. This issue has been addressed by interfacing a comprehensive kinetic stability code¹ with a model tokamak MHD equilibrium² with a separatrix and an X-point. The equilibrium here takes into account the enhanced local shear effects near the separatrix and is basically an extension of the familiar "s- α " model³ whose finite- β properties are primarily governed by the magnitude of the local pressure gradient. Fully electromagnetic calculations of the dominant toroidal microinstabilities were carried out using for input parameters the edge data obtained from careful measurements of H-mode and L-mode PDX tokamak discharges⁴. The results obtained indicate that the proximity of the separatrix to the magnetic surface considered has a significant stabilizing influence. This effect is considerably stronger for the H-mode cases with their characteristically steeper edge profiles. In particular, the finite- β -modified drift-type electrostatic modes as well as the kinetically-calculated MHD ballooning modes are expected to be stable over a region extending several centimeters inside the separatrix for the H-mode profiles, but only over a much smaller region for the L-mode profiles. These enhanced local stability properties near the separatrix thus serve to support the notion that thermal transport properties in H-mode plasmas are reconcilable with microinstability-based models.

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

¹ G. Rewoldt, W. M. Tang, and R. J. Hastie, Princeton University Plasma Physics Laboratory Report PPPL-2367, Phys. Fluids (in press).

² C. M. Bishop, Nucl. Fusion **26**, 1063 (1986).

³ J. W. Connor, R. J. Hastie, and J. B. Taylor, Phys. Rev. Lett. **40**, 396 (1978).

⁴ B. LeBlanc and B. Grek (private communication); R. E. Slusher, C. M. Surko, J. F. Valley, T. Crowley, E. Mazzucato, and K. McGuire, Phys. Rev. Lett. **53**, 667 (1984), cf. Fig. 2.

NUMERICAL SOLUTION OF AMPERE'S LAW IN THREE-DIMENSIONAL TOROIDAL DOMAINS*

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An important part of the nonvariational algorithm for calculating MHD equilibria¹⁻³ is the solution of Ampere's law in a three-dimensional toroidal domain. A simple ansatz reduces $\text{curl}(\mathbf{B}) = \mathbf{J}$ to a single Poisson equation with a Neumann boundary condition. The numerical solution of this Poisson equation is quite subtle, since different discretizations drastically affect the convergence properties of the nonvariational algorithm. We discuss these different discretizations and the results of numerical experiments that test the convergence properties of these discretizations as functions of radial and angular resolutions. The best discretization treats the contravariant components of the gradient of the unknown as fundamental quantities, uses both integer and half-integer meshes, and uses analyticity to differentiate accurately the leading radial powers of Fourier coefficients near the magnetic axis.

¹A.H. Reiman and H.S. Greenside, Comput. Phys. Commun. 43, 157 (1986).

²A. Salas, A.H. Reiman, and H.S. Greenside, this meeting.

³A.H. Reiman, H.S. Greenside, this meeting.

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

CONVERGENCE PROPERTIES OF A NONVARIATIONAL 3D MHD EQUILIBRIUM CODE*

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We have systematically studied the convergence properties of a new 3D MHD equilibrium code which employs a novel nonvariational algorithm.¹ For our benchmark cases we have employed a three-dimensional stellarator equilibrium and a two-dimensional Solovév equilibrium. In these studies we have typically continued iterating the code well beyond the point where it converges in order to test its stability under different modes of operation.

We have studied the effects on the numerics of different gauges for solving Ampere's law, of solving for the incremental solution, of underrelaxation, and of radial filtering. Complete numerical stability requires a small amount of radial filtering of the high frequency components in the solution (the equivalent of dealiasing for the radial finite difference scheme). This is consistent with our earlier observation that dealiasing was crucial in the Fourier representation of the angular variation. We have also studied the effect of varying mesh resolution in radial and angular directions.

¹A.H. Reiman and H.S. Greenside, Comput. Phys. Commun. 43, 157 (1986).

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THREE-DIMENSIONAL MHD EQUILIBRIUM WITH MAGNETIC ISLANDS*

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We have developed a three-dimensional MHD equilibrium code which is capable of describing magnetic islands and stochastic field lines. Initially directed towards stellarator equilibria¹, the code has now been modified to handle islands and stochastic regions with finite current. This modification allows us to solve for tokamak equilibria with islands. Self-consistent island solutions have also required an additional coordinate transformation to eliminate the resonant components of the magnetic coordinates before entering the Poisson solver.

We present self-consistent MHD equilibrium solutions with large islands, and discuss the convergence properties of the code for such equilibria. Analytical cylindrical force-free equilibria with islands are used to test the accuracy of the code in determining island widths.

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NUMERICAL RESULTS ON FIELD ERRORS IN THE PRESENCE OF RFP EQUILIBRIA*

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Recently, a 3D MHD code has been used to study the interaction of a set of vacuum field errors with an RFP equilibrium. Two different equilibria have been used. The field-error perturbations are added to the equilibrium fields and the combination is time-advanced by the code.

The first equilibrium is stable and is not allowed to evolve by resistive diffusion. (This excludes the RFP dynamo.) Previous results have shown that the field error-equilibrium combination reaches a quasi-steady state. For small initial field errors, the final-state field perturbations scale linearly with their values at the wall. They are unaffected by the alteration of the initial perturbation profiles, depending only on the values at the wall. The amplitude of a field perturbation at its resonant surface is sometimes reduced ($m=0$) and sometimes enhanced ($m=1$) in the final state.

New results include an analysis of the numerical data. The magnitudes of perturbed flow velocity and field have been studied as functions of the free parameters in the equations-magnetic Reynold's number and viscosity. Empirical scaling laws have been determined. The scale invariance properties of the model equations have been examined. They show that the empirical scaling laws are consistent with the equations, but may be constrained by the form of the boundary conditions.

The second equilibrium is unstable; the RFP dynamo is active. The presence of the field errors alters the behavior of the unstable plasma modes. Growing instabilities in the plasma phase-lock to the field errors. The field errors also shift the mode spectrum.

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"Stability Properties of Shaped Tokamaks With Energetic Alpha Populations"*

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Energetic alpha populations can influence the stability of ballooning modes through coupling between the trapped alpha precessional drift and ballooning mode frequency. This mechanism has been examined in some detail for circular cross section tokamaks where it was found to lower the first stability beta limit and, in some cases, close off access between first and second stable regimes. Such effects are of particular interest for noncircular ignition tokamaks such as the Compact Ignition Tokamak (CIT) which will operate near the ballooning stability limit and where the fusion produced α -pressure gradient can be a substantial fraction of the background gradient. We have extended this analysis by including a general equilibrium solution with elongated and triangular flux surfaces in the kinetic ballooning analysis. An isotropic model for the alpha pitch angle distribution has been used and the energy and pitch angle dependence of the precessional drift frequency is retained. The complete coupled integro-differential mode equations have been solved using an iterative procedure; based on this solution it has been possible to also develop an approximate method which should be reasonably accurate, but be computationally more efficient for carrying out parameter studies. Results of these studies over a range of alpha and background plasma parameter regimes relevant to CIT will be discussed.

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TRANSITIONS FROM PASSING TO TRAPPED IN STELLARATORS AND RIPPLED TOKAMAKS*

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Here we compare numerical and analytic approximations for phenomena which occur at a boundary layer between trapped and passing particles in stellarators and tokamaks with ripple. Previously, the toroidal adiabatic invariant has been shown to give orbits which agree well with solutions to the full guiding center equations of motion for both passing and trapped particles [J. S. Tolliver, C. L. Hedrick, and L. W. Owen, *Bull. Am. Phys. Soc.*, **31**, 1389 (1986)]. For transitional particles, which sometimes transit a field period and sometimes are trapped in the ripple of a boundary field period, the agreement is also good except at a boundary layer. Here we focus on phenomena in which some incident passing particles are reflected at the boundary layer to become passing particles with the opposite sign of the parallel velocity, and some particles cross the boundary layer to become trapped. In particular, we compare numerical calculations of the fraction trapped to analytic expressions for the fraction given previously [John R. Cary, *Bull. Am. Phys. Soc.*, **31**, 1388 (1986)].

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INSTABILITIES OF AN RFP WITH A RESISTIVE SHELL**G. Marklin****Los Alamos National Laboratory****Los Alamos, New Mexico 87545**

Ideal MHD growth rates have been computed for instabilities of an RFP with a thin-resistive shell and a modified-bessel-function equilibrium. Growth times of a small fraction of τ_{shell} are common, but there exist optimum values of θ for which growth times can be several times τ_{shell} . ($\tau_{shell} = \mu_o \sigma \delta a$, σ = conductivity, δ = thickness, a = minor radius.) The optimum theta depends on the cutoff radius and $\theta_{opt} \approx 1.5$ at $r_c = .7$.

NUMERICAL PROBLEMS OF THREE-DIMENSIONAL MHD SIMULATIONS

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Numerical difficulties that the authors have encountered in the implementation of the MHD model in cylindrical (r, θ, z) geometry using a Fourier series representation in the θ, z coordinates are discussed. These can be placed in two broad categories and are listed briefly as:

1. Numerical Implementation of Regularity as $r \rightarrow 0$ (or $\psi \sim r^2 \rightarrow 0$ using mean-field poloidal flux as a radial coordinate).
 - a. Direct second-order differencing of terms $\frac{1}{r} \frac{\partial ru}{\partial r}$ is an inconsistent approximation for $r \sim \Delta r$ on either a staggered or nonstaggered grid.
 - b. $\frac{u}{r} + \frac{\partial u}{\partial r}$ can be consistently centered differenced on an unstaggered, but not on a staggered, grid.
 - c. Characteristics of convection and Alfvén wave operators are hyperbolas $r^2 t = \text{const.}$ and hyperbolas plus straight lines $\frac{r^2}{t} = \text{const.}$, respectively, in the $r^2 - t$ plane, as $r^2 \rightarrow 0$. Thus, equations are lower order at $r = 0$ and couple radially only through lower order spatial terms. (This separates $-r$ or $-\psi$ from $+r$ or $+\psi$ in hyperbolic systems of equations.)
 - d. $m = 1$ components of (V_r, V_θ) and (B_r, B_θ) and their evolutionary equations become identical as $r \rightarrow 0$. Remove this linear dependence by defining $V_\pm = V_r \pm V_\theta$ etc., and use $V_\pm, B_\pm$ as new dependent variables uniformly. (Shifts difficulty to coefficients - write equations to have "lumped" coefficients that have regular behavior as $r \rightarrow 0$.)
 - e. Will discuss treatment of $r = 0$ ($\psi = 0$) as a passive point (low order extrapolation) or as an active time evolved point (finite volume methods to avoid decoupling).
2. Role of Dissipation and Dispersion for Numerical Stability.
 - a. Simple review of need for dissipative schemes for non-constant coefficient hyperbolic equations.
 - b. Semi-implicit time differencing—as a k -dependent variable mass (or $S(k)$) algorithm versus filtering.
 - c. Consider minimum dissipation to stabilize leapfrog scheme for Alfvén waves - resistivity versus viscosity.
 - d. Discuss merits of the direct addition of numerical diffusion to a numerical algorithm versus the filtering of coefficients and nonlinear terms that enter the equations resulting in lower needed level of direct diffusion.

Abstract

Applications of the BETA Equilibrium, Stability and Transport Codes to the Design of Stellarators.

F. Bauer, O. Betancourt, P. Garabedian and M. Wakatani.

A book under this title will be published by Academic Press Boston later this year. A dozen equilibrium and stability runs will be included that illustrate examples of current interest for the design of major new stellarator experiments. A Monte Carlo transport code will be listed that calculates ion and electron confinement times from the equilibrium output. This code will be made available at the NMFECC when the book appears. A procedure is given to calculate the electric field from quasineutrality equations so as to explain the anomalous loss of electrons.

Anomalous Transport in Toroidal Plasmas

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Anomalous transport in toroidal plasmas arises from the presence of more complicated magnetic and electric fields than are required by the macroscopic equilibrium of the plasma. If one knew these fields, then the transport coefficients, calculated by classical methods, would be correct except for the direct transport of energy by the fields (which is usually considered negligible). The limitation of this procedure is the lack of knowledge of the field perturbations, but there are a number of features that are generally accepted whether the perturbations are due to microinstabilities or due to macroscopic effects such as tearing modes. In particular, the frequencies and the wave numbers of the perturbations satisfy $\omega \gtrsim \omega_*$, $k_{\perp} \rho_i \gtrsim 1$, and $k_{\parallel} \rho_i \ll 1$, which imply that the magnetic moments of both the ions and the electrons are conserved and that the particle trajectories obey drift equations. The drift equations imply that if magnetic surfaces exist, particles can only cross a surface if there is a spatial variation in the field strength or the electric potential in the surface. If surfaces fail to exist, then particles can also cross the toroidal flux surfaces by moving along the field lines. There are a number of experimental measurements that would help determine nature of the field perturbations: If the transport coefficients for particles and electron heat are comparable, then the ions must be affected comparably to the electrons by the perturbations. Cross terms, such as the transport of ion energy by convection, give information on which particles in a roughly Maxwellian distribution of energies are primarily causing the transport. (The use 5/2 for this number is purely conventional, but one would expect the number to be positive and of order of magnitude unity.) The difference in transport coefficients between high and low energy particles, such as beam, and bulk, ions or runaway, and bulk, electrons, helps determine whether magnetic, or electric potential, perturbations are responsible for transport. Enhanced transport of passing particles, such as beam ions, relative to the trapped particles is indicative of the loss of surfaces. The presence, or absence, of anomalous current profile spreading also addresses the issue of surface existence. If all plasma transport coefficients are approximately equal, then one explanation would be intermittent stochasticity of the field lines. In this model, each magnetic surface in the plasma is broken during the course of a confinement time, but at any particular time only a fraction of the surfaces are broken. Theoretical calculations, using Monte Carlo codes as well as analytic calculations, could clarify the level and type of perturbations that are required to obtain the observed features of plasma transport.

ICRF Ponderomotive Force Effects on Tokamak Equilibrium and Stability*

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Large amplitude ICRF waves can give rise to a ponderomotive force which modifies the usual MHD description of the plasma. This effect is being examined both to assess its role in rf heating experiments and to deliberately exploit it to enhance tokamak performance. When the ICRF waves are applied uniformly, so that the ponderomotive force is normal to the flux surfaces, the energy principle for kink and ballooning modes is supplemented by the addition of direct ponderomotive and nonlinear sideband terms. For the ballooning modes¹ rf field amplitudes exceeding a critical threshold level provide a path from first to second stability in the usual s - α diagram. The global stability of the plasma depends on the spatial profiles of the rf wave. Two types of solutions of the rf wave equation, corresponding to fast wave and Bernstein wave couplers, have been examined in a cylindrical plasma model. Near the edge region of the plasma where highly evanescent surface-wave structures can exist, ponderomotive effects occur at modest values of the $E_{\parallel}$ component of the rf wave. For the near fields of an antenna that is localized poloidally and/or toroidally, the ponderomotive force can also influence the MHD equilibrium causing distortion of flux surfaces. This effect is calculated perturbatively in a low beta model that treats the equilibrium modifications as driven zero-frequency kink modes. For toroidally localized antennae, the edge flux surfaces remain good when the poloidal localization is not severe.

1. D. A. D'Ippolito, J. R. Myra and G. L. Francis, Science Applications International Corporation Report #SAIC-86-1981/PRI-108 (December 1986).

*Work supported by U.S.D.O.E. contract DE-AC03-76-ET53057.

THE PENETRATION OF THE LOWER-HYBRID-DRIFT INSTABILITY TO THE FIELD NULL IN THE FIELD-REVERSED CONFIGURATION

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It is observed experimentally that the flux-confinement time in Field-Reversed Configurations (FRC's) is anomalously short, implying an anomalously high resistivity in the field-null region. The Lower-Hybrid-Drift Instability (LHDI) is one microinstability thought to be contributing to anomalous-field penetration in the sheath region of the FRC. In the linear, local theory, this instability will not be active at the field null since the growth rate is proportional to B . Linear nonlocal theories have shown that eigenfunctions driven by conditions in the sheath region can extend toward the field null, but that the eigenfunction vanishes before reaching the null. Nonlinear simulations, however, have shown that the instability can penetrate to the null in the case of low ion to electron-mass ratio and high-drift parameters and that the penetration rate decreases or even vanishes as the mass ratio increases or the drift parameter decreases.

This research examines the penetration rate in the high-mass ratio, low-drift parameter regime. Preliminary results are that the instability penetrates to the field null, but that the rate of penetration is greatly reduced compared to the low-mass ratio, high-drift parameter regime.

NEUTRAL BEAM INJECTION AND PLASMA DIFFUSION IN A TOKAMAK*

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Two-dimensional numerical plasma simulations on plasma diffusion in a plasma, subject to neutral beam injection in a slab geometry¹ have been extended to a tokamak-like toroidal geometry. Motions of both the thermal and neutral particles are followed in time in a given toroidal and poloidal magnetic field but in a self-consistent electric field arising from the injection and ionization of the neutral particles. Neutral particles injected across or along the toroidal magnetic field are assumed ionized via various ionization processes (charge exchange, electron impact, ...) which generate an electric field associated with the polarization at the edges of a plasma as well as due to the toroidal drifts.

Results of the two-dimensional simulations indicate that a large amplitude electric field is generated in a plasma ($T_p \leq e\phi_0 \ll E_b$) associated with the neutral injection where E_b is the injection energy and T_p is the plasma temperature. The induced electrostatic potential is not azimuthally symmetric in a poloidal plane and has an up-and-down asymmetry. Such a potential can cause particle diffusion across a magnetic surface.

In addition to the self-consistent plasma simulations, the orbit of a single particle has been followed in a given magnetic and electric field. It is found that if the electrostatic potential has an up-and-down asymmetry, then the particle can drift away from the magnetic surface thereby causing plasma diffusion in the presence of collisions or plasma turbulence.

Scaling of the plasma diffusion and its magnitude will be studied and reported.

¹H. Okuda and S. Hiroe, Diffusion of a Plasma Subject to Neutral Beam Injection, PPPL-2388 (Phys. Fluids, April 1987)

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CALCULATING THE SELF-CONSISTENT KINETIC TILTING EIGENFUNCTION FOR AN FRC

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For long, elliptical FRC's the displacement vector for the internal tilt mode in MHD can be reduced to an axial displacement that depends on the flux label ψ alone. We use this representation in the Vlasov-fluid model (collisionless ions, massless fluid electrons) to calculate the kinetic stability of this mode. Our earlier calculations assumed the MHD eigenfunction as a trial function for the kinetic model.^{1,2} For the self-consistent kinetic calculation we represent the axial displacement as

$$\xi_z(\psi, \omega) = \sum_{i=1}^N a_i(\omega) f_i(\psi).$$

The functions $f_i(\psi)$ are unevenly spaced cubic splines. In the dispersion equation, we use this representation and the Galerkin procedure to obtain a matrix problem for determining the coefficients $a_i(\omega)$. The eigenfrequencies satisfy $\det D(\omega) = 0$, where $D(\omega)$ is the dispersion matrix. Appropriate measures have been taken to ensure that we approximate the solution of the dispersion equation that is regular at the O-point. Results will be presented for an FRC equilibrium as a function of s , where s measures the number of local ion gyroradii between the field null and the separatrix.

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2. D. C. Barnes, J. L. Schwarzmeier, H. R. Lewis, and C. E. Seyler, *Phys. Fluids* **29**, 2616 (1986).

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Ideal Stability Limits of DIII-D Equilibria*

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An unoptimized sequence of equilibria expected in the β increment path for DIII-D with $\kappa \lesssim 2$, $\delta \leq 0.5$ to 0.7 , covering the parameter range of $0.5 < \ell_i < 1.2$, $2 < I/aB < 3.5$, $\beta \lesssim 10\%$ is used to investigate the profile effects on the MHD stability. The global $n=0$ and $n=1$ modes are investigated by using GATO. The localized ballooning mode is investigated by using MBC. It is found that a wall distance of $1.25 < b/a < 2$ can completely stabilize the $n=0$ axisymmetric mode. The internal kink mode at central elongation ~ 2 requires a central $q_0 \gtrsim 1.15$. The localized ballooning mode at constant I/aB , however, favors a flat current profile due to the close coupling of q_s and ℓ_i for the configuration. At very low ℓ_i , the external kink is destabilized. Thus, the optimized β [1] is reached at low ℓ_i value. The effect of the external wall on the optimized β value is also shown.

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

[1] F.J. Helton, L.C. Bernard, and J.M. Greene, Nucl. Fusion **25**, 299 (1985).

PROFILE CONSISTENCY: GLOBAL AND NONLINEAR TRANSPORT*

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The main implication of the "Principle of Profile Consistency" is that the transport coefficients that conform to it depend on the global properties of the plasma column.¹ Another implication is that there are two kinds of physical processes involved: one that reconstructs the canonical electron temperature profile once this is severely disrupted, such as when a massive pellet is injected in the plasma column, and one that determines the rate of electron energy transport under nearly steady state conditions. Thus a variety of transport equations that can describe both processes have been considered, including one that involves the presence of an inward flow term that is difficult to justify on the basis of the properties of known micro-instabilities and is not suitable to represent the wider range of relevant experimental information now available. Instead it is more appropriate to introduce an effective thermal conductivity that has a nonlinear dependence on the electron temperature gradient such as

$$\kappa_{\text{eff}} = \left[\kappa_s^2 + \kappa_F^2 \left(\frac{a^2}{T_e \alpha} \frac{\partial T_e}{\partial r} + 1 \right)^2 \right]^{1/2}$$

where the canonical electron temperature profile is represented by $T_e^C(r) = T_{e0} \exp(-\alpha)$, $\alpha \equiv \alpha(r^2/a^2)$, a is the plasma (minor) radius, κ_s is the thermal conductivity that persists when T_e is completely relaxed on the $T_e^C(r)$ profile, and κ_F the coefficient corresponding to the fast process that rearranges $T_e(r)$ when it is forced to depart from $T_e^C(r)$. Considering $\kappa_F^2 > \kappa_s^2$ and under steady state conditions the peak value T_{e0} is determined by the "minimum departure condition"

$$\int_0^{\alpha_b} d\alpha' \left\{ \left[\bar{S}_e a^2 / (4\alpha T_e^C) \right]^2 - \kappa_s^2 \right\}^{1/2} / \kappa_F = 0, \quad ,$$

where $\bar{S}_e(r) \equiv (2/r^2) \int r' S_e(r') dr'$, $S_e(r)$ is the electron energy source and $\alpha_b \equiv \alpha(r=a)$. Therefore κ_s need not be function of the profile of $S_e(r)$ in order to enforce profile consistency and can be used directly as derived from a nonlinear theory of the type of microinstability deemed to be responsible for it. One that is considered of special interest for this is the so-called ubiquitous mode² that is driven by the electron temperature gradient and produces thermal energy transport without corresponding particle transport. In the case where only ohmic heating is present, the adopted diffusion coefficient $D_{\text{th}}^e = \kappa_s / n$ is

$$D_{\text{th}}^e \approx 6 \times 10^{17} (a/r) B_\theta / (n T_e) (Z_*/A_i) (q_s R)^{-1/2} \text{ cm}^2/\text{sec}$$

where T_e is in keV, $B_\theta(r)$ in kG, n in cm^{-3} , R in cm, $Z_*/A_i \equiv v_s^2 / (T_e/m_p)$, m_p the proton mass and v_s the ion-sound velocity of the considered plasma. When injected heating is prevalent this form of D_{th}^e is extended to include the fact that

$$8\pi / (B_\theta r)^2 \int_0^r dr'^2 d(n T_e) / d \ln r$$

becomes the limiting factor and the D_{th}^e acquires the scaling $D_{\text{th}}^e \propto 1/B_\theta$.

*Sponsored in part by the U.S. Department of Energy.

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**Internal Kink Modes in Elongated Tokamaks
with Flat Rotational Transform**

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Experimental observations at JET indicate that the sawtooth collapses in that tokamak are due to an ideal MHD internal kink instability which occurs at rather low values of β . This low β ideal instability can be explained¹ by the fact that q is almost constantly equal to 1 inside the $q = 1$ rational surface. We have carried out an analytical and numerical study of the linear stability of internal kink modes in low β plasmas having a flat (and nearly equal to 1) q -profile over a sizable inner portion of their domain, and elongated cross section. We show that, at finite aspect ratio, these configurations are unstable and that the plasma elongation has a large destabilizing effect. We also show that, under these conditions, a significant number of higher radial unstable modes all of them having $m = 1$ and $n = 1$ poloidal and toroidal wavenumbers can be excited.

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* Work supported by the U.S. Department of Energy DE-AC02-78ET51013.

TRANSPORT THEORY FOR FLUCTUATING ELECTRIC FIELDS IN TOROIDAL PLASMAS*

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Fluctuating electric fields are ubiquitous in toroidal confinement devices such as tokamaks, stellarators, and reverse field pinches. The inherent helical structures of the fluctuations break the toroidal symmetry of tokamaks and reverse field pinches. From this point of view, the transport properties of toroidal symmetric systems with fluctuating electric fields are similar to those of stellarators. A transport theory for fluctuating electric fields in toroidal plasmas is constructed by using the methods developed for neoclassical stellarator transport theory. Flux-force relationships are derived from the momentum and heat flux balance equations with the emphasis of the symmetry breaking effect introduced by the helical structures of the fluctuating electric fields. The term that is responsible for the transport is $\tilde{N}\tilde{E}$, where $\tilde{N}$ and $\tilde{E}$ are fluctuating density and electric fields. As an example, transport fluxes that include particle and heat fluxes, parallel current, modification on plasma resistivity, and toroidal momentum confinement time are calculated for the low frequency fluctuations in the plateau regime. The results show that in tokamaks with modest fluctuating level ($e\tilde{\Phi}/T_e \gtrsim 1\%$) and mode number ($m \sim 10$) electron particle and heat fluxes can be larger than those obtained from neoclassical theory. There are particle and heat pinch fluxes associated with the off-diagonal terms. The bootstrap current induced by the fluctuating electric fields flows in the opposite direction on different sides of the mode rational surface. The toroidal momentum confinement time is reduced from its neoclassical value. The modification on the neoclassical resistivity becomes important if $e\tilde{\Phi}/T_e \gtrsim \epsilon$, the inverse aspect ratio. The qualitative features of the theory are consistent with experimental observations. The results obtained by removing the low frequency assumption will also be presented.

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ICRF MODELLING STUDIES FOR TFTR*

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A computational package has been constructed to model forthcoming ICRF plus neutral beam heating experiments on TFTR. The package is comprised of interlocking or stand-alone codes which treat the coupled problems of rf power deposition, fast ion resonant acceleration and slowing down and radial transport. Several forms of the package may be used which permit various approximations of the wave propagation and damping analysis suitable for large devices, and which greatly facilitate on-line analysis of experimental data. In addition, an optimized Fokker-Planck solver allows modelling in two velocity dimensions of the beam slowing down in conjunction with rf resonant diffusion at either the fundamental or second harmonic frequencies. Relevant fast ion transport and loss mechanisms are included in this model. Resulting power deposition profiles to the background electrons and ions are used in conjunction with existing transport codes to complete the modelling package. Considerable effort has been expended to formulate contracted, numerically tractable forms of the mode conversion and damping equations appropriate for tokamak geometry with two dimensional equilibrium gradients and realistic antenna configurations. Preliminary benchmark studies and plans for future model development will be discussed.

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BOOTSTRAP CURRENT AND SAWTOOTH ACTIVITY IN TOKAMAK

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ABSTRACT

A local variation of the pressure gradient drives a current profile

modification through the Bootstrap current, $\delta j \sim j_B \sim -\sqrt{\frac{r}{R}} \frac{1}{B_0} \delta \left(\frac{\partial p}{\partial r} \right)$;

on a time scale τ_B , much shorter than the global resistive time τ_R .

LINEAR MODE CONVERSION AND THE OPERATOR THEORY OF WAVE MECHANICS

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Abstract

The linear mode conversion regime for the approximate dispersion relation $(\omega - \omega_1(x, k))(\omega - \omega_2(x, k)) = \eta$ occurs near $x = x_c$, $k = k_c$ such that $\omega_1(x_c, k_c) = \omega_2(x_c, k_c)$. Cairns and Lashmore-Davies have recently expressed the associated energy flow in terms of a single parameter which involves η and the partial derivatives of ω_1 and ω_2 . In this paper, a different, wave mechanical approach is used to obtain the same result. The process of linear mode conversion is discussed using the system $L\Psi = i\partial\Psi/\partial t$, where L is a Hermitian operator. The degeneracy of plasma modes, and their coupling by warm plasma corrections in an inhomogeneous plasma, is dealt with using first order perturbation theory. Simple coupled first order differential equations for the wave amplitudes follow, which can be integrated directly to give the required expression for the energy flow.

SHERWOOD THEORY MEETING 1987

**Hot Electron Interchange Mode
at Arbitrary Ion Cyclotron Frequency***

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The stability of layer modes is analyzed for a cylindrical model with the hot particle pressure profile nearly constant from the origin to a radius r_0 , where it then rapidly decreases to zero. Curvature is modeled by an embedded radially decreasing magnetic field. The background plasma is treated as an MHD fluid. A new, relatively simple dispersion relation is derived for arbitrary ω/ω_{ci} , which reduces to the known result in the low-frequency limit. The dispersion relation is for a global mode, but it resembles a WKB dispersion relation previously derived.¹ The hot particle interchange mode is destabilized when the density ratio of hot electrons to ions exceeds a critical value that depends on the ratio of curvature frequency to ion cyclotron frequency. The simple stability criterion can also be derived for an electrostatic, sharp boundary gravity model. The stability windows in parameter space is discussed.

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Numerical Properties of a Finite- β Gyrokinetic Plasma*

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As reported earlier,¹ gyrokinetic plasma in the electrostatic limit possesses some very attractive numerical properties. This is the result of the gyrophase averaging process which eliminates space charge waves from the governing equations, and, consequently, removes the parametric dependence of ω_{pe} and λ_D from the simulation plasma. Thus, the scheme not only enables us to use a much smaller number of particles in the simulation, but also affords us with the luxury of a much longer time step and a much larger grid spacing, characterized by ω_H and ρ_s , respectively, where $\omega_H \equiv (k_{||}/k)(m_i/m_e)^{1/2}\Omega_i$, $\rho_s \equiv \rho_i(T_e/T_i)^{1/2}$, and ρ_i is the ion gyroradius. The present study has shown that magnetic perturbations associated with shear-Alfven waves can further improve the numerical properties of the gyrokinetic plasma. Specifically, according to the fluctuation-dissipation theorem, the noise level for the initial fluctuation is drastically reduced due to the finite- β effects. For $\beta \gg m_e/m_i$ and $(k_{\perp}\rho_s)^2 \ll 1$, the fluctuation amplitude of $|e\phi(k)/T|$ depends only on the number of simulation particles within one wavelength of the mode. In addition, even longer time step can be realized in the simulation, since $\omega_A \ll \omega_H$, where $\omega_A \equiv k_{||}v_A/[1+(ck/\omega_{pe})^2]^{1/2} \equiv \omega_H/[1+(\omega_{pe}/ck)^2]^{1/2}$ is the shear-Alfven frequency. Furthermore, finite- β effects can totally remove the restrictions on grid spacing. Thus, realistic particle simulation of tokamak discharges with the present generation of supercomputers is now feasible. The work on the finite- β nonlinear gyrokinetic equations is presently in progress.²

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Nonlinear Finite- β Gyrokinetic Equations*

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A self-consistent set of nonlinear equations (gyrokinetic-Poisson-Ampere system) for finite- β plasmas has been developed. The present work is a natural extension of the electrostatic gyrokinetic equations,^{1,2} which are the basis for a number of recent particle simulation studies of microinstabilities in tokamaks. Unlike the existing nonlinear gyrokinetic equations for finite- β plasmas,³ the present formulation is in the phase-space preserving form and it also satisfies the underlying conservation laws of the original Vlasov-Maxwell system. As such, the resulting equations are amenable to particle simulation studies. The numerical advantages for such an approach are reported in an accompanying paper.⁴

In the present study, based on the ordering of $\omega/\Omega_i \sim k_{\parallel}/k_{\perp} \sim e\Phi/T \sim \delta B/B \sim v_E/v_{th} \sim O(\epsilon)$, we have arrived at a set of equations which is valid for $k_{\perp}\rho_i \sim 1$, for the linear as well as the nonlinear terms. A reduced set of equations with $k_{\perp}\rho_i \ll 1$ for the nonlinear terms has also been obtained. The relationship between these nonlinear gyrokinetic equations and the reduced MHD equations as well as the possibility of using gyrokinetic particle simulation for studying MHD instabilities will be discussed.

*Work supported by U. S. D. o. E. Contract No. DE-AC02-76-CHO-3073.

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Neoclassical Effects on Resistive MHD Modes*

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The effects of rotation damping and bootstrap current production on several phenomenon is investigated.

- 1) For typical parameters, the $m = 1$ tearing mode can be stabilized when FLR is included. This can help explain recent experimental observations that q is less than one on axis.
- 2) Ergodic magnetic limiter experiments on the TEXT tokamak show evidence of self-consistent electrostatic potential effects which can be explained using rotation damping.
- 3) Bootstrap current driven linear modes¹ are shown to be stabilized by viscosity. A nonlinear Rutherford Island instability^{2,3,4} is still possible, however. Nonlinear thresholds will be examined.

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Hall Thermal Effects on Plasma Transport*

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Hall thermal effects exist in both momentum equations and energy equations for ions and electrons in the two-fluid theory developed by Braginskii. It has been shown** that the Hall thermal electron effect improves the plasma equilibrium condition and an equilibrium can exist in the presence of a vacuum even without a mass or energy source (or sink), contrary to the results from one-fluid theory. To study the Hall thermal effects on plasma transport phenomena, we extend the Alternating Dimension Formulation originally developed by Grad to the two-fluid theory including the Hall thermal effects for axisymmetrical geometries. The Hall thermal electron effect modifies the Ohm's law, and therefore the poloidal magnetic flux no longer diffuses at skin time but at a time scale which also depends on heat conductivities. In addition to the Hall heat flows, the ion and electron entropy equations, as cast in standard diffusive type form, are also modified by the Hall thermal electron effect through the convection and diffusion of toroidal magnetic flux. There are four diffusion time scales and their differences with those obtained from one-fluid theory will be discussed. Plasma behavior near the vacuum will also be examined.

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Optimized Matrix Solution Packages for Use in Plasma Physics Codes*

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Elliptic and parabolic partial differential equations (PDE's) which arise in plasma physics and other applications may require implicit solution techniques. The sparse matrix equations which result from finite difference or finite element discretization often share a common structure. We report on a package of matrix solvers for such equations. The matrix sparsity patterns are 9-banded in two dimensions; 7, 15, 19, or 27-banded in three dimensions; and block-banded for coupled PDE's. We use solution techniques based on the conjugate gradient method. Storage of the matrix elements by diagonals allows many of the operations to vectorize directly. Other operations are treated by multitasking and indirect vectorization as appropriate.

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Spheromak Heating by Lower Hybrid Pulses

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An experiment to heat a compact toroid (CT) device using an intense pulse of lower hybrid (LH) radiofrequency energy is underway. The heating is done using a short (100 us) pulse of high-power (100 MW) microwaves at lower hybrid frequencies. Theoretical issues are the nonlinear effects involved in the RF propagation and absorption, and in the transient energy loss due to the oxygen impurity line radiation during and following the pulsed RF heating. The results of a non-LTE radiation code calculation will be presented, and a parametric coupling effects involving the RF pulse propagation will be discussed. A global energy balance model for this heating scenario will be shown.

Subject: Compact Toroids, Spheromaks

THERMAL DIFFUSION IN TURBULENT FLUID PLASMAS*

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We consider the heat transport due to fluid plasma turbulence and present some properties of the turbulent thermal diffusion derived from the nonlinear resistive MHD equations with finite heat conductivity and viscosity. This is an extension of Ref. 1.

Assuming the fluctuations are small, we derive the set of equations describing the dynamics of the mean quantities, where, in the limit of small resistivity, the turbulent diffusion appears in the form of $\text{div} (K \text{ grad } T_0)$, where K is a positive function.

As a special case, we consider the reduced equation of a particular class of modes. It is shown that if the pressure gradient is small enough, the turbulent thermal diffusion is again expressed as $\text{div} (K \text{ grad } T_0)$.

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THE DYNAMO EFFECT AT LOW AND HIGH BETA*

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In low beta fusion plasma, the dynamo effect does not drive current. It can be described by a hyper-resistive term in Ohm's Law, caused by tearing mode turbulence. The turbulence also produces anomalous heat transport. A 1-D model is constructed which can reproduce RFP experimental and 3-D computational results for $F(\theta)$ and $\beta(\theta)$.

At very high beta, the dynamo effect drives current. Analytic and 3-D numerical studies have been made of a model in which the plasma velocity field is stochastic. The final state of the magnetic field appears to be independent of the resistivity, but the relaxation rate depends on resistivity to the $-1/3$ power. Studies have also been conducted for single-mode velocity resonances. In this case, boundary layers with width scaling as the resistivity to $-1/3$ power are observed.

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STATUS OF TJ-II DEVICE

TJ-II Group (Presented by C. Alejaldre)

Association CIEMAT/EURATOM, CIEMAT, MADRID (SPAIN)

TJ-II is a helical axis stellarator of heliac type to be built at CIEMAT (MADRID) that has obtained Phase-I preferential support from EURATOM in April 1986.

TJ-II has four periods, 1.5 m of major radius, an average toroidal magnetic field of 1 T and an estimated average plasma radius of 0.20 m. It allows high t values simultaneous with magnetic well and a great flexibility to change the working t value, magnetic well depth, magnetic ripple at axis etc ... (1).

A study is done to assess ECRH heating possibilities showing the position of cut-offs and resonances on the peculiar magnetic configurations of TJ-II, revealing a total different situation from that in tokamaks or usual stellarators. The highly localized region of wave absorption in the plasma, suggests the use of ECRH as an efficient method of temperature profile control in the device (2).

Evaluations for the confinement times, energy balances, equilibrium temperatures and maximum β values for the different TJ-II heating scenario are shown, obtaining central β values for the different heating schemes of 0.8% for 400 kW ECRH, 2.6% for 2 MW NB and 9% for 5 MW NBH, while the resulting confinement times are 4, 9 and 6 ms respectively.

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Nonlinear Effects on the Deposition of FEL Power in Alcator-C*

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With the high-intensity FEL electron-cyclotron power that will be used to heat the Alcator-C plasma in the Microwave Tokamak Experiment (MTX), nonlinear effects will compete with thermal effects in the absorption of the incident power.¹ It is expected that the peak power will be in the range of 4 to 8 GW with pulse duration of 5×10^{-8} sec and a repetition rate up to 5 kHz. Three parameters govern the nonlinear effects. For O-mode deposition at the fundamental electron cyclotron resonance, the parameters are:

$$p_1 = \frac{mc^2}{T_e} \left[\frac{N_{\perp}}{\sqrt{2}} \frac{v_{\parallel}}{c} \frac{E_{\parallel}}{B_0} \right]^{2/3}, \quad p_2 = \left(\frac{mc^2}{T_e} \right) \left(\frac{2\pi v_{\parallel}}{\omega_{ce} w} \right), \quad p_3 = \left(\frac{mc^2}{T_e} \right)^{1/2} N_{\parallel}$$

where w is width of the microwave beam. In this study, the code TORAY² is used to examine the dependence of the heating deposition profile on incident power level and on the width of the incident Gaussian beam. The beam is modeled with an appropriate bundle of rays which are traced through the plasma. We find that nonlinear effects can cause significant reduction in the power deposition when the incident peak-power levels in MTX exceed 1 GW with $\hat{n}_e = 1 \times 10^{14} \text{ cm}^{-3}$ and $\hat{T}_e = 2 \text{ keV}$. However, at higher central densities or temperatures the primary result of the nonlinear effects is broadening of the ECH deposition profile in MTX.

We also examine nonlinear effects on current-drive efficiency in MTX. In the limit $p_1 \gg 1$, the efficiency is obtained from an adjoint calculation that uses the Green's function from Ref. 3 (which includes trapped-particle and relativistic effects) and an ECH operator modeled as sources and sinks at oscillation extremes. In the opposite limit $p_1 \ll 1$, the calculation of Ref. 3 applies directly.

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

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OPTIMIZATION OF THE BOOTSTRAP CURRENT IN STELLARATORS*

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The magnitude of the bootstrap current is important for studying equilibrium and stability properties of stellarators. We calculate the bootstrap currents for several stellarator configurations such as ATF, Heliotron-E, and W7AS. We also compare the magnitude of the bootstrap current of stellarators with that of tokamaks for a fixed value of plasma β but with appropriate safety factor q and aspect ratio A . We find that stellarators usually have a smaller value of bootstrap current than tokamaks.

For a given constraint on the relative magnitudes of the Fourier amplitudes of magnetic field strength B , we can find a configuration which has the smallest value of the bootstrap current. Several constraints will be considered. Since the bootstrap current is not directly related to the particle flux, the configuration that has optimized value of bootstrap current may not have optimized value of particle flux. The compatibility of optimizing these two transport properties will be discussed.

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Ion Cyclotron Emission Calculations Using a 2D Full Wave Numerical Code*

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Measurement of radiation in the HF band due to cyclotron emission by energetic ions produced by fusion reactions or neutral beam injection promises to be a useful diagnostic on large devices which are entering the reactor regime of operation.¹ A number of complications make the modelling and interpretation of such measurements difficult using conventional geometrical optics methods. In particular the long wavelength and lack of high directivity of antennas in this frequency regime make observation of a single path across the plasma into a viewing dump impractical. Pickup antennas effectively see the whole plasma and wall reflection effects are important. We have modified our 2D full wave ICRH code² to calculate wave fields due to a distribution of energetic ions in tokamak geometry. The radiation is modeled as due to an ensemble of localized source currents distributed in space. The spatial structure of the coherent wave field is then calculated including cyclotron harmonic damping as compared to the usual procedure of incoherently summing powers of individual radiators. This method has the advantage that phase information from localized radiating currents is globally retained so the directivity of the pickup antennas is correctly represented. Also standing waves and wall reflections are automatically included.

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On The Second Harmonic Layer of an Obliquely Propagating Extraordinary Wave in a Tokamak*

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The absorption rate of an electromagnetic wave is easy to estimate in the weak absorption limit.¹ However this approach is not adequate for the extraordinary mode around the second harmonic resonance due to the possibility of mode conversion to the strongly damped quasi-electrostatic mode (a so-called Bernstein mode). We must know detailed dispersion curves for the extraordinary mode and the Bernstein mode. In most previous theories²⁻⁴ of the second harmonic heating in a tokamak, the dispersion relations were studied for complex $k_{\perp}$ and a fixed real $k_{\parallel}$, assuming a tokamak plasma is plane-stratified. Recently, Imre and Weitzner developed an extensive theory⁵ for the second harmonic absorption including the mode conversion effects based on the same assumption. However, $k_{\parallel}$ of a propagating wave is not invariant in a tokamak and could be complex. In fact, $k_{\parallel}$ changes in the same degree as $k_{\perp}$ or more in a realistic tokamak. Since it is impossible to obtain complex solutions for $k_{\parallel}$ and $k_{\perp}$ from one complex dispersion relation, some studies were done for complex ω using the fact that the solution of the dispersion relation in a boundary value problem is equivalent to that in an initial value problem if the dissipation is small. However, we have found that the dispersion curves for complex ω are quite different from those obtained for a complex $k_{\perp}$. The propagation angles for the mode conversion to occur and the energy deposition profiles due to the converted wave are drastically different in these two approaches. Thus, no appropriate theories applicable to the vicinity of the second harmonic resonance in a tokamak presently exist. The problem is important for a wave of small $k_{\parallel}$ or for waves in low temperature or low density plasmas, because the absorption is negligible except at the vicinity of the resonance in these cases.

We will argue the need of a more appropriate theory and also show an example dispersion curve for the extraordinary mode obtained by solving for imaginary parts of k when real parts are given by a cold plasma theory. Unfortunately, this approach is not applicable to the Bernstein mode.

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SURFACE WAVES IN A MAGNETIZED PLASMA SLAB*

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Surface wave propagation in a magnetized plasma slab has been studied through simulation techniques. Two different boundary conditions have been considered. In the case of a sharp boundary, the particles are assumed to be specularly reflected at the plasma-vacuum interface. For the free boundary, the plasma is considered to be confined by ion inertia and the magnetic field. The existence of generalized surface Bernstein waves has been observed in the case of a sharp boundary and reported earlier. A continuum spectrum between cyclotron harmonics with distinct dips at $n\omega_c$ begins to appear as the system size becomes large. A line spectrum is also observed and splitting of the spectral lines is observed for the sharp boundary as well for the free boundary. In the case of a free boundary a continuous spectrum has also been observed for $k_y = 0$ ($k_y \parallel$ surface) mode; this corresponds to oscillation of the sheath layer near the plasma-vacuum interface. In addition to the generalized surface Bernstein waves other surface waves with complex k_x appeared above the upper hybrid frequency.

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Effect of Poloidal Field on Ion Bernstein Waves*

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We have analyzed the effect of a weak poloidal field on the propagation and absorption of ion Bernstein waves. The plasma is assumed to fill uniformly a conducting cylinder of radius a and to carry a constant current density, resulting in a poloidal field which varies linearly with radius r and is much smaller than the "toroidal" (or, in this geometry, axial) field. If the ion cyclotron radius r_{ci} is small compared to the scale length, L , of the electrostatic potential $\phi(r)\exp[i(k_z z + \omega t)]$, an expansion in r_{ci}/L converts the integral equation for ϕ into a second order differential equation for the radial profile $\phi(r)$. The principal effect of the poloidal field is a shift in the cyclotron resonance frequency due to the helical character of the magnetic field lines. Since the shift is proportional to $\mathbf{v} \cdot \mathbf{B}/B$ it has the same effect as a shift in the parallel component of $\mathbf{k}$, resulting in an asymmetry between waves propagating in opposite axial directions and a modification of the absorption at the cyclotron layer. In addition, the radial dependence of the component of $\mathbf{k}$ perpendicular to the local $\mathbf{B}$ field creates a kind of "centrifugal barrier" which keeps waves propagating inward from the edge from reaching the center. It also causes the radial component of group velocity and, with it, the coefficient of the second derivative term to vanish at a certain radius, resulting in a wave resonance which restricts the propagation to a radial band. Numerical solutions of the single particle equations of motion in the presence of a driving electrostatic field, confirming the predicted frequency shift, will be presented, as will solutions of the differential equations for several cases of interest.

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CIT: Ideal MHD and Design*

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This paper will address those CIT physics guidelines and design objectives that are best understood and achieved by studying ideal MHD equilibrium and stability properties of various configurations. An alternate CIT design concept has been developed. This design has decoupled ohmic and poloidal field-shaping coil systems and all the poloidal field-shaping coils are inside the toroidal field coil. It is thus similar to the DIII-D design. Highly triangulated limiter and divertor equilibrium solutions can be obtained and the solution spaces are robust. Vertical stability results will be discussed. It is possible to obtain acceptable diverted equilibria that are stable to $n=0$ modes with an assumed super-conducting wall at constant distance a (plasma minor radius) from the plasma. The highest β_c at which diverted equilibria are stable to $n=1$ modes with a wall at infinity will be discussed.

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SHERWOOD THEORY MEETING 1987

Application of the Free Energy Principle $\delta^2 F$ for Determining Tokamak Stability via Reduced Fluid Models*

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The $\delta^2 F$ free energy principle is a generalization of δW that is applicable to kinetic systems and equilibria with flow. It provides a method for determining stability that goes beyond the spectral method, guaranteeing nonlinear stability, and it enables a generalization of the notion of negative energy modes¹. This principle has been applied to the stability of tokamak equilibria in the context of a variety of reduced fluid models². These models are generalizations of reduced MHD that allow for finite ion Larmor radius physics and other effects related to compressibility and electron adiabaticity. Thresholds for stability are obtained for equilibria with poloidal and toroidal flow and the effects of compressibility and ion gyro-physics are elucidated. Simple examples will be presented that point out when spectral stability theory fails to yield a reliable answer.

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Spurious Excitation of Edge Lower-Hybrid Resonance by ICRF Couplers*

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Most analysis of the coupling characteristics of ICRF antennas assume, for simplicity, that the plasma density in contact with the antenna structure is sufficiently high so that the electrostatic lower-hybrid resonance point (i.e., where $\epsilon_{\perp} = 0$) is not encountered for the given excitation frequency. Motivated by the increasing interest to perform high harmonic experiments, and to consider ICRF heating of high toroidal field devices requiring large excitation frequencies (hence favoring the occurrence of $\epsilon_{\perp} = 0$), the present theoretical study examines the possible role that such a resonance can play in the tenuous edge plasma surrounding an ICRF coupler. The formulation is based on the separation of electrostatic and inductive effects by using the scalar and magnetic potentials (ϕ , $\underline{A}$). The vacuum $\underline{A}$ generated by the antenna structure is used as a source term that generates a charge separation in the plasma due to the edge density gradient; this charge acts as an in-situ antenna that excites the spatially localized lower-hybrid resonance. The amplitude of the resonant electric field (limited by collisions) can be quite large, but does not contribute significantly to the antenna loading resistance because the edge density is low. The role of the resonant electric field as a possible source of fast ions and edge modifications is considered.

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Stabilization of Long Wavelength Ballooning
Modes by Poloidal Flow*

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We find that low mode number ballooning modes can be stabilized by a poloidal flow. When the flow speed is about 10% of the poloidal Alfvén speed, the critical beta for instability of $n=3$ modes is significantly increased. When the flow speed is increased to 20% of the poloidal Alfvén speed, the mode is stable for all beta. The approach and results resemble an earlier study of finite Larmor radius stabilization¹. We use large aspect ratio, high beta tokamak reduced MHD. A constant toroidal velocity can be added without affecting the result, since we can transform to the rotating frame.

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*Work supported by U.S. Department of Energy, Grant No. DE-FG02-86ER53223.

1987 SHERWOOD THEORY CONFERENCE

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**RAY TRACING ANALYSIS OF THE MODE CONVERTED
ION-BERNSTEIN WAVE IN ICRF HEATING***

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We have carried out a detailed numerical ray trajectory analysis in toroidal geometry of the ion-Bernstein wave (IBW) that is excited by the mode-conversion of the externally launched fast wave in ICRF heating of tokamak plasmas. We find that parallel (to the total magnetic field) wave numbers ($k_{\parallel}$) which are very small for the launched fast wave, are significantly enhanced along the IBW so that the wave can Landau damp on the electrons. This enhancement of $k_{\parallel}$ occurs for short radial distances of propagation and could help explain the observed strong electron heating by ICRF waves in tokamaks. The ray trajectory analysis is for a hot maxwellian plasma and the gradients in temperature, density, toroidal and poloidal magnetic fields are included in the WKB sense. Along with the detailed numerical analysis, a simplified analytical model will also be presented that helps explain the results and shows the role of the poloidal magnetic field in the enhancement of the parallel wave numbers.

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Transport Simulations of the Compact Ignition Tokamak*

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Simulations of Compact Ignition Tokamak (CIT) operation have been carried out with the 1-1/2-D BALDUR transport code. Various transport models of both empirical and semi-empirical (such as the Tang thermal diffusion model¹) origin are used, and their impact on CIT ignition assessed. The previous work² is extended to include a more realistic startup phase in which the plasma shape and ICRH heating profile are ramped up with the magnetic field and plasma current. The code now includes bootstrap current as well as improved sawtooth and ballooning-enhanced transport models. The effects of profile peaking, limits on density and β , variations in device parameters, and the L- or H-mode character of the transport scaling law on CIT ignition are examined with both the 1-1/2-D code and a simpler 0-D transport code.

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

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The Effect of Peaked Profiles on Ignition*

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It is becoming increasingly clear that peaked density and temperature profiles, which maximize the fusion power production ($\propto \langle n^2 T^2 \rangle$) relative to thermal energy content of the plasma squared ($\propto \langle nT \rangle^2$), are conducive to ignition in those tokamak reactor designs which otherwise only marginally ignite.¹ There are a variety of inducements, however, which impell the tokamak reactor designer toward broad profiles, in conflict with the above assessment. Maximizing current, for example, which maximizes beta, global Ohmic heating rate, and L-mode confinement time, also produces a broad sawtooth mixing region and broad T_e profile, as magnetic diffusion approaches steady state. The transition to H-mode confinement is generally observed to produce broader density and temperature profiles with relatively modest increase in central values. Once a plasma is hot enough and dense enough to ignite, it is difficult to centrally fuel the plasma (to maintain a peaked density profile) by deep pellet or neutral beam injection. Flat profiles tend to optimize beta relative to MHD ballooning and kink modes. We explore these issues using 1-1/2-D BALDUR transport code simulations with self-consistent models for sawteeth and ballooning modes.

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

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Numerical MHD Simulation of an RFP with Resistive Wall*

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Behavior of a reversed-field-pinch with thin resistive shell and an outer conducting wall is being studied using a 3D MHD code. The shell is modeled by a jump condition on the radial magnetic field perturbations much like the Δ' analysis of tearing modes. Vacuum solution of the fields between the shell and outer wall is obtained analytically.

Initial computations eliminating the nonlinear terms agrees with analytical linear calculations¹. With large outer wall radius and axial field reversal, the RFP is linearly unstable to long wavelength $m=1$ external kink modes. Calculations with Modified Bessel Function Modeled equilibrium indicates growth rates of up to $3/\tau_w$ at high theta values ($\tau_w = a\Delta/\eta_w$ where a =minor radius of plasma, Δ =thickness of shell, and η_w is the shell resistivity).

Present investigation is aimed at the nonlinear evolution of these modes and subsequently, their implications for experiments.

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¹Presented at APS plasma conference, 1986.

SHORT WAVELENGTH DRIFT-ALFVEN VORTICES

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We study the nonlinear dynamics of short wavelength drift-Alfven waves. These waves, with the characteristic frequency between the electron and ion gyrofrequencies ($\Omega_e > \omega > \Omega_i$) can be excited in nonuniform, hot magnetized plasmas, in which ions can be regarded as essentially unmagnetized, while the electrons are strongly magnetized. In the fully nonlinear regime, general traveling solution is found in the form of a superposition of single and multiple vortex forms, and in a special case it reduces to the standard double vortex soliton (modon). Modons are weakly interacting, and for a class of parameters they do not interact at all, unless their cores overlap.

MHD Stability Limits for Elongated Tokamaks

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The MHD stability of elongated tokamaks is limited by a variety of instabilities. Axisymmetric modes impose limits on the peakedness of the current profile and the position of a conducting wall. External non-axisymmetric current-driven kink modes impose limits on the width of the current profile and on the total toroidal current. Internal $n=1$ current-driven modes impose further limitations on the current profile. Non-axisymmetric modes can also be driven unstable by the Pfirsch-Schlüter current at high β , and these, along with purely pressure-driven (ballooning) modes, can limit the achievable β .

The effects of the equilibrium current and pressure profiles and of shaping of the poloidal cross-section (elongation and triangularity) on the stability limits are investigated in detail. It is shown, in particular, that moderate elongation alone (≤ 3) can significantly enhance the achievable current over that for an equivalent circular cross-section, and that, although the β can also be enhanced, the enhancement does not follow the optimistic extrapolations to these elongations of the linear scaling law with current. When strong triangularity is coupled with elongation, however, the β limits are significantly higher, though still below the optimistic extrapolations of the linear scaling law.

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ANOMALOUS TRANSPORT DUE TO BROKEN SYMMETRY*

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There appears to be no lack of instabilities and other magnetic perturbations sufficient to break axisymmetry in a Tokamak, producing small magnetic islands and a small degree of stochasticity in electron orbits. A Hamiltonian guiding center formalism¹ is used to investigate to what degree such symmetry breaking could be self regulating, by a poloidal smoothing of the current distribution caused by the incipient stochasticity.

¹R.B. White, in Statistical Physics and Chaos in Fusion Plasma, Edited by C.W. Horton and L.E. Reichl, John Wiley and Sons 1984.

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

TWO DIMENSIONAL SIMULATIONS OF A RAMPED STARTUP OF A TOROIDAL REVERSED-FIELD PINCH

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The modeling of the reversed-field pinch is of particular importance for the design of the four megampere reversed-field pinch ZTH to be constructed and operated in a new Los Alamos Confinement Physics Research Facility (CPRF). The aim of this study is to obtain a fully toroidal, axisymmetric, time dependent simulation of the RFP discharge including the resistive vacuum liner, conducting shell, field coils, and external circuitry with feedback control. This will be used for making predictions of the plasma-circuit response when the plasma beta and profiles change with time. Such calculations will allow comparisons and extensions of the present simplified modeling used for the design of ZTH.¹ The approach discussed here involves modifications of a toroidal tokamak code.² These modifications allow (1) toroidal-field reversal (2) plasma relaxation including a global modeling of the dynamo effect and (3) a scheme for modeling the losses for the RFP.

The plasma relaxation is modeled by adding a term to a mean-field ohm's law^{3,4} to give the required dynamo effect to prevent the loss of positive toroidal field by resistive diffusion when the reversed field is maintained by the external toroidal field coils. In the absence of definite formulas for the transport losses in the RFP with its dynamo action, the transport losses are accounted for by programming the plasma pressure and density in accordance with predictions from present RFP experiments. Comparisons of the code results with experiments, 3-D cylindrical MHD code results,⁵ and the previous engineering design modeling of ZTH will be given.

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Zero Dimensional CIT Ignition Studies With Drift Wave Turbulence Models*

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CIT ignition studies have been largely based on Kaye-Goldston¹ empirical scaling laws for anomalous energy losses. In the present work we report the results of zero-dimensional CIT ignition studies which model the anomalous losses using drift wave turbulence scaling laws. The model is calibrated to fit data from Doublet III ohmic and beam heated L-mode discharges.² Both electron and ion anomalous loss mechanisms are included through simple drift wave models for trapped electron and ion temperature gradient mode turbulence. The dissipative trapped electron scaling accounts for the neo-Alcator scaling in low density ohmic discharges. The ion temperature gradient mode scaling accounts for high density ohmic saturation of confinement time; an *ad hoc* q form factor is used with this scaling to convert favorable B scaling of τ_E to favorable I scaling in beam heated discharges. Solving the steady state power balance equation obtains density versus temperature contours parameterized by the input power, with the ignition curve requiring no auxiliary heating in the steady state. We find that for nominal CIT design parameters ($a = 45$ cm, $R = 130$ cm, $B = 10$ T, $I = 10$ MA) an inordinate amount of auxiliary power ($P > 100$ MW) is required to reach ignition if the dissipative trapped electron mode scaling is operative³; η_i mode anomalous losses raise the power requirements further. This is in contrast to the conclusions derived using empirical scaling laws which have no power degradation in the neo-Alcator scaling. The critical power for ignition is studied for various plasma sizes, and magnetic fields subject to the constraints on collisionality and plasma beta. In addition, we show that a change in the scaling of the dominant anomalous energy loss mechanism can affect the topology of the density, temperature contours. Finally, we compare results of the zero-dimensional model with transport code simulations, using the anomalous transport model² previously applied to present generation tokamaks.

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Motion Near the Separatrix of the Drift Wave Hamiltonian*

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The motion near the separatrix of the drift wave Hamiltonian with two waves and no shear is investigated. The system is studied in the frame of the largest wave and the second wave is treated as a perturbation. An approximate value of the Melnikov-Arnold integral is calculated analytically for part of the separatrix for both large and small $\Omega = \omega''/\omega_b$ where ω'' is the frequency of the second wave and $\omega_b = ck_x k_y \phi_m / B$. Numerical evaluation of the integral shows that the two asymptotic expressions have a common range of validity. The integral is then used to show that the flow close to the separatrix can be represented by the standard map. The collisionless stochastic diffusion coefficient D is finally evaluated numerically as a function of Ω and the strength of the wave amplitude ratios. In the presence of one wave the diffusion is completely determined by the residual Coulomb collisions D_0 . We show¹ that for large Peclet (Reynolds) number $P = v/kD_0 = c\phi_m/BD_0$ that the diffusion is given by $D = 1.06 (D_0 c\phi_m/B)^{1/2}$. For coherent convective cells the diffusion is with $e\phi_m = T_e$ the diffusion is $(D_0 D_B)^{1/2}$ with $D_B = cT_e/eB$.

¹M.N. Rosenbluth, H.L. Berk, I. Doxas, W. Horton, *Effective Diffusion in Laminar Convective Flows*, IFSR 261 (1987).

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Inverse Problem for Incremental Synchrotron Radiation†

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A method is proposed by which plasma synchrotron emission from tokamaks may be used to infer the two-dimensional azimuthally symmetric electron distribution function $f(v_{\parallel}, v_{\perp})$. Attaining significant velocity-space resolution in a direct approach to this inverse problem is difficult for two reasons: one, the frequency of the radiation emitted is not particularly sensitive to the electron perpendicular velocity, especially for nonrelativistic electrons; and two, a single radiation detector yields only the one-dimensional spectral energy density $I(\omega)$, yet two-dimensional velocity information $f(v_{\parallel}, v_{\perp})$ is to be inferred. More information would be available were an array of soft x-ray detectors placed around the tokamak minor cross-section, but that is not practical.

We solve instead a simpler, but, as we show, very useful, problem. Suppose that rf or other power induces in the plasma a velocity-space flux $\Gamma(\mathbf{v}, t)$, and we measure the *incremental* radiation emitted by the perturbed distribution. We are at liberty, however, to modulate or otherwise control the time-dependence here; so suppose we impose an impulse $\Gamma = \mathbf{S}(\mathbf{v})\delta(t)$. The incremental radiation now decays in time as the electrons suffer collisions, but this time decay is revealing. For example, radiation associated with fast electrons decays slowly, in fact as $1/v^3$, which finely resolves the electron speed. The evolution of the radiation on the slow collisional time scale can be written as

$$I(\omega, t) = - \int d^3v \, \psi(\omega, \mathbf{v}, t) \nabla \cdot \mathbf{S}(\mathbf{v}), \quad (*)$$

where ψ is the Green's function that solves the Fokker-Planck equation for the radiation response, and is available numerically and in limits relevant here analytically. It remains now to find the 2-D flux $\mathbf{S}(v_{\parallel}, v_{\perp})$, given the adjoint solution ψ and the 2-D experimental data $I(\omega, t)$, which is available from a single detector. This inverse problem exploits the ability of soft x-ray detectors to resolve finely time behavior on the collisional time scale; since this measurement is made at each frequency, orders of magnitude more information on $\mathbf{S}(\mathbf{v})$ becomes available. The mathematical inversion of (*) exploits the properties of the four-dimensional kernel $\psi(\omega, \mathbf{v}, t)$.

Having the details of $\mathbf{S}(\mathbf{v})$ is an end in itself for many problems in rf current-drive and heating. Real-time feedback for waveguide-phasing is contemplated here. Moreover, knowledge of $\mathbf{S}(\mathbf{v})$ together with theories of wave damping allows us to infer $f(v_{\parallel}, v_{\perp})$. More exciting, solution of the inverse problem posed here can provide a diagnostic for the loop voltage on axis, which is difficult to measure by other means.

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FREQUENCY SPECTRUM OF RESISTIVITY-GRADIENT-DRIVEN TURBULENCE DUE TO SHEARED RADIAL ELECTRIC FIELD*

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In order to explain the origin of experimentally observed frequency and wavenumber spectra of turbulent fluctuations in the tokamak edge,^{1,2} the previously studied resistivity-gradient-driven turbulence model³ is extended to include the frequency Doppler-shift effect on the basic mode due to a sheared radial electric field. The computational studies have been carried out with the three-dimensional nonlinear resistive MHD code 'KITE'.⁴ The results indicate that the frequency and wavenumber spectra of turbulent fluctuations are in a fair agreement with experimentally deduced spectra. We will discuss the shear flow driven effects (Kelvin-Helmholtz) on resistivity-gradient-driven turbulence for experimentally relevant regime.

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Gigaflop Speed Algorithm for 3D Plasma Equilibrium and Stability Problems*

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In the calculation of 3D equilibria of toroidal plasmas the use of finite dimensional sets of basis functions is often desired in the representation. Spectral representations are typically chosen in the two angle-like coordinates because they naturally satisfy the periodicity requirements. Finite difference or finite element techniques are used to treat the radial coordinate. One such application is the three dimensional generalization of the ERATO group of codes for the computation of plasma equilibria and the subsequent linear stability calculations. The discretization of the equilibrium equations in terms of these representations leads to a block-tridiagonal matrix equation in which the blocks are dense sub-matrices. We have found that these equations may be solved rapidly by using a multitasked cyclic reduction procedure on the Cray-2 computer. Using this technique we have recently built a new code PAMS (PARallelized Matrix Solver) that has been further optimised by the use of fast vendor supplied subroutines. Speeds well in excess of 1 gigaflops have been measured for the entire code. The matrix structure for the stability calculations is not simply block-tridiagonal; we show a special reduction procedure that transforms these equations into the required form to which the PAMS solver is applied. We like to point out that this method is intended for multiprocessor computers and would not be a method of choice on a uniprocessor.

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Abstract for 1987 Sherwood Theory Meeting

PLASMA SIMULATIONS ON THE MARK III HYPERCUBE COMPUTER*

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Two distinct plasma simulation models are being implemented on the Caltech/JPL MARK III Hypercube[1] computer to study the applicability of this architecture to large scale plasma physics computations. The first code is a two-dimensional drift wave turbulence model and the second is a one-dimensional electrostatic particle simulation model.

The MARK III Hypercube consists of 32 parallel processors connected topologically as a five dimensional cube. Each processor has 4 megabytes of local memory and a peak performance of 10 megaflops. There is no shared memory.

The two-dimensional plasma turbulence model solves the well known Hasegawa-Mima equation for drift waves. In this model, the drift wave turbulence is decomposed into fourier components with wave vectors lying in the plane perpendicular to the magnetic field. The various fourier components are coupled nonlinearly. The coupled modes obey an equation of the form

$$\frac{\partial A_{m,n}(t)}{\partial t} + i\omega_{n,m} A_{m,n}(t) = \sum_{n'} \sum_{m'} C_{n-n',m-m'} A_{m',n'}(t) A_{n-n',m-m'}(t)$$

The computation has been parallelized by assigning a fraction of the fourier modes to each processor and having each processor solve the above equation for its' assigned modes. At the start of each time step, the updated mode amplitudes are passed to all of the other processors to allow the evaluation of the mode coupling term needed to advance the mode amplitudes to the next time step. Calculations with $n_{max} = m_{max} = 15$ (112 coupled fourier modes plus complex conjugates) using one processor require approximately 640 secs while the same calculation using all 32 processors require approximately 30 secs. Efficiency should increase for larger calculations.

Implementation of the 1 - d electrostatic particle simulation model has just begun. This code has previously been benchmarked on many other large computers[2]. In the first Hypercube implementation, the particle calculation, but not the electric field calculation, is done in parallel. (The particle calculation generally takes roughly 90% of the cpu time.) The particle calculation is parallelized by assigning a fraction of the particles to each processor and having each processor "push" its' assigned particles. Timings for the benchmarked calculation will be presented.

* Work supported in part by DOE/OFE and in part by Sandia National Laboratory

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Second Harmonic Ion Cyclotron Resonance in a Tokamak*

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ABSTRACT

In large tokamaks, where geometrical optics is a good approximation at ion cyclotron frequencies, wave propagation near resonance is usually studied based on the approximation of a perpendicularly stratified medium. In this work, we do not assume perpendicular stratification, but we do continue to assume that the geometrical optics parameter is small. We derive wave equations for the two cases where B_p/B_t is very small and when it is moderately small. Outside the parameter ranges described we conclude geometrical optics holds and only weak damping occurs. For the smallest range of values of B_p/B_t we find that the wave equation is modified from the standard fourth order system usually used. For slightly larger values of B_p/B_t a much more intricate integro-differential equation is relevant. Simple general properties of these systems are presented.

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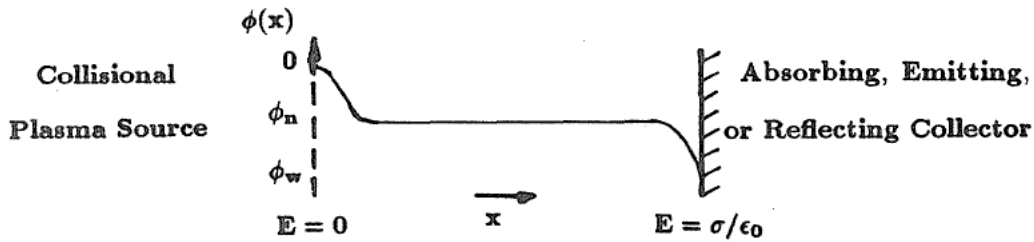
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Collector Sheath and Source Sheath in a Collisionless Finite Ion Temperature Plasma with Secondary Electron Emission and Ion Reflection at the Bounding Surface¹ - LOU ANN SCHWAGER, *Plasma Theory and Simulation Group, Electronics Research Lab, University of California, Berkeley CA 94720.*

For an electrically floating surface in contact with a plasma, our analytical and numerical results for the surface potential and plasma transport differ considerably from those using traditional Bohm sheath analysis. The finite sheath region between a collisional warm plasma and the confining, interacting surface is modeled numerically with electrostatic particle simulation using PDW1 and analytically with a plasma-sheath equation. The model and assumed boundary conditions along with a typical potential profile are shown below. For the purely absorbing surface, we derive the plasma-sheath equation for the boundary conditions shown below. The collisional plasma source can have arbitrary ion/electron ratios of mass and temperature. Our technique extends the analysis of Kuhn² with a temperature ratio $T_i/T_e = \tau = 1$ to include an arbitrary value for τ .

Simulation results after equilibration and our time-independent, analytic theory exactly agree. When compared with works such as that of Chodura³ and Stangeby⁴ who rely on a Bohm type of semi-infinite sheath model, our derivation predicts a lower wall potential ϕ_w for a mass ratio of 1836 and $\tau = 1$; this difference is within 20%. Our ϕ_w found with $\tau = 1$ and the ϕ_w derived by Stangeby and Chodura for $\tau = 0$ agree to within 2%. For $\tau \geq 1$ our results for the ion drift velocity v_D entering the collector sheath are within 4% of Stangeby's assumption that this velocity, normalized by the ion thermal velocity v_t is $(1 + \frac{1}{\tau})^{1/2}$. For $\tau \ll 1$ our results show a much smaller v_D ; e.g. with $\tau = 0.1$ and a mass ratio of 1836, $v_D/v_t = 1.8$. Note that the presheath region, which we define below by ϕ_n , has a zero electric field; hence the "presheath acceleration" of the ions occurs entirely in the source sheath within a few Debye lengths from the plasma source. Our potential results for a large range of mass and temperature ratios compare well with Emmert⁵ who analytically models the plasma-sheath equation for a bounded system with Boltzmann electrons.

For electron-induced secondary electron emission, we have simulated emission beyond field reversal at the plate to emission coefficients Γ over 100%. For emission values up to the critical coefficient at field reversal, our dependence of ϕ_w on Γ for $\tau = 1$ compare well to that of Hobbs and Wesson⁶ who assume $\tau \ll 1$. For the reflection of plasma ions, we have simulated reflection coefficients R up to 80%. The wall potential decreases as we increase R . Despite an ion-ion two-streaming interaction, which generates substantial potential fluctuations, the time-averaged values for ϕ_w and transport agree well with our time-independent analysis which assumes $\tau \ll 1$.



¹ This work supported by U.S. DOE Contract No. DE-FG03-86ER53220.

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BOUNDARY CONDITIONS FOR THE HIGH DENSITY Z-PINCH

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Attempts at a one-fluid simulation of the High Density Z-Pinch using the Moving Finite Element (MFE) method have encountered difficulties caused by boundary conditions at the plasma-vacuum interface. While other codes have had similar problems, adaptive methods like MFE are especially susceptible to numerical instabilities because they attempt to move the adaptive grid into the rough edge region caused by inconsistent boundary conditions, making matters worse rather than better. These problems have motivated a careful analysis of the behavior of the fluid equations in the neighborhood of the edge, leading to the formulation of boundary conditions which are consistent with the internal equations as they approach the edge. The key idea is to impose Neumann boundary conditions, specifying the slopes of the dependent variables slightly in from the edge, rather than the values of the variables at the point where the density vanishes. This choice of boundary conditions allows the code to run quickly and smoothly, with no hint of numerical instability, no artificial density floor, and no need for dissipation of any kind, either natural or artificial. For the case of an expanding column of ideal gas, comparison to an analytical self-similar solution is possible. Expansion by a factor of 10 from the initial radius takes less than 5 seconds of Cray cpu time with better than 1% accuracy.

COLLISIONAL PLASMA PRESHEATH*

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A kinetic approach is used to calculate the electrostatic potential variation in the sheath and presheath regions of a collisional plasma contained between perfectly absorbing walls. Ion-ion collisions are assumed to be the dominant collisional process and are included in the analysis through a Bhatnagar, Gross and Krook^[1] operator which conserves particles, momentum and energy. The mean free path for ion-ion collisions is assumed to be large compared to the Debye length and independent of both velocity and position. The plasma is one-dimensional with a Boltzmann distribution of electrons and no magnetic field effects are included in the analysis.

An equation for the potential variation in the presheath region is derived and solved numerically. In the collisionless limit, the solution corresponds to previous analytical results.^[2] As collisionality is increased, the magnitude of the potential drop in the presheath region is increased while the potential drop in the sheath region is decreased. The ion distribution function and the ion particle and energy fluxes into the sheath are also calculated. The ion distribution function at the sheath edge satisfies the generalized Bohm criterion.^[3]

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SHERWOOD THEORY MEETING 1987

Neoclassical MHD Turbulence*

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Recently, resistive MHD equations were extended to include high temperature regimes in tokamaks.¹ These neoclassical MHD equations in banana-plateau regimes give both qualitative and quantitative corrections to resistive MHD instabilities.

The resistivity gradient driven turbulence² now can tap energy in the density gradient as well as the temperature gradient as a free energy source due to the density dependence of the neoclassical resistivity. Nonlinear calculations show the density gradient enhances this instability. This effect is most significant when $\nu_* \sim 1$. Fluctuation levels of $\tilde{T}e/Te$, $\tilde{n}/n_0$, $e\tilde{\phi}/Te$, and $\tilde{B}_r/B_0$ are determined. Typically, $\tilde{n}/n_0 > \tilde{T}e/Te$ and Boltzmann relation, $e\tilde{\phi}/Te = \tilde{n}/n_0$ breaks down, which are consistent with results of experimental studies.³

Neoclassical MHD equations also give rise to new kinds of instabilities such as the bootstrap current instability. The methods developed in the course of previous studies⁴ of the structure of resistive interchange modes can be applied. Results of nonlinear studies of the bootstrap current instability will be presented.

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Computation of the Parallel Viscosity For
Transport Purposes In Stellarators

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Abstract

The final goal of this research is the self-consistent computation of interesting "observables" such as transport fluxes, parallel flows, Pfirsch-Schluter and bootstrap currents and the ambipolar electric field, in the low collision frequency regimes in stellarators. We attack the problem numerically and utilize ideas employed in a bounce-averaged transport study done by Mynick and Hitchon^{1,2} and concepts based on the moment formalism developed by Hirshman.³ The moment approach points out the importance of the "parallel viscous force density" $\langle \mathbf{B} \cdot \nabla \pi \rangle$ in that it is the quantity that gives rise to the bootstrap current and the so-called "axisymmetric flux". In order to find $\langle \mathbf{B} \cdot \nabla \pi \rangle$, two important requirements must be satisfied: the collision operator must be momentum conserving and the distribution function must be allowed to vary along a field line. The first point necessitates adjustment of the collision operator in the code of Refs. 1 and 2. The second remark requires interpretation. The bounce-averaged output $\bar{f}$ of the Mynick-Hitchon treatment is averaged over the helical ripples, but not over the "tokamak-like" variation of the $\mathbf{B}$ -field. Hence this $\bar{f}$ does contain important parts of $\langle \mathbf{B} \cdot \nabla \pi \rangle$, if not all of them (given that $C(f)$ is momentum conserving). The direct contribution to the viscosity of the ripple trapped particles (and the helical ripple induced perturbation on the "tokamak-like" blocked particles) is evidently not included. Its importance is expected to be small, but examination of this issue is asked for. Here, we intend to present the results of $\langle \mathbf{B} \cdot \nabla \pi \rangle$ due to $\bar{f}$ alone.

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* This work was supported in part by the Department of Energy Grants DE-FG02-86ER53201 and DE-FG02-86ER53216.A001.

RESISTIVE EVOLUTION OF PLASMAS WITH IMPERFECT MAGNETIC SURFACES.* G. Miller, Los Alamos National Laboratory.--The theory of resistive evolution of plasmas is extended to include plasmas with imperfect magnetic surfaces, that is, plasmas having magnetic field lines that wander stochastically. A simple, but not entirely realistic or, indeed, self-consistent limit of this theory, where the magnetic field is assumed ergodic, meaning that a single field line sweeps out an entire plasma volume, has already been discussed.¹ In the present work a formalism is created to describe magnetic field line structure in a general way, allowing a general evaluation of magnetic flux constraints. The equations expressing flux constraints, along with the plasma equilibrium equation, constitute the mathematical model that is solved to determine the evolution of the plasma.

The degree to which magnetic field lines wander stochastically is described by parameters of the theory. Varying these parameters allows description, in a unified way, of the complete range possible from perfect magnetic surfaces to effectively ergodic field lines. Sample calculations of magnetic field evolution in the Tokamak and pinch for various degrees of stochasticity will be presented.

An immediate result of this model is that, for plasmas with stochastic field lines (but not in the ergodic limit), the plasma current density has a filamentary structure. In certain cases, with no external source of error magnetic field, the source of stochasticity of the magnetic field would seem to be the fine-scale irregular distribution of current filaments within the plasma itself.

This theory is compared with experimental data from ZT-40M. The measurements that were most useful in constraining parameters of the theory were magnetic probe measurements carried out for low current discharges with and without F- θ pumping.² Good agreement between model and data, including discharges driven by F- θ pumping, is obtained when parameters of the model (one positive profile) are chosen properly. The conclusion from this work is that reversed field pinch behavior is consistent with simple laws of resistive evolution.

Finally, the application of this theory to the problem of resistive evolution of helical magnetic islands in the reversed field pinch will be discussed.

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MHD EQUILIBRIUM AND STABILITY CONSIDERATIONS FOR CIT^{*}

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CIT, Compact Ignition Tokamak, is a Dee shaped device with a low aspect-ratio. Since it is primarily an ignition experiment, design considerations tend to be conservative. In this spirit it has been suggested the q-edge be limited to have values greater than 3.5. This has been based on the observation that experiments in non-circular shaped plasmas have tended to disrupt when q-edge falls below this value. Equilibrium considerations indicate that in non-circular tokamaks, geometric effects play an important role in determining the current and hence safety-factor profiles. This has implications for CIT. Thus if the q-axis is constrained to be close to unity, the q-edge value plays an important role in determining the details of the shear. For example, a low q-edge (2.2) would introduce a large low-shear region near the axis. This has adverse implications for ideal MHD stability, as it sets up conditions favorable to destabilizing the infernal modes. Increasing q-edge can improve the stability properties. We shall examine this effect in conjunction with the role of the geometry in determining the current profile and hence the stability limits, for a variety of geometries in the vicinity of the CIT reference design point.

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DECIMATION OF BETCHOV'S MODEL OF QUADRATIC TURBULENCE: COMPARISON WITH THE DIA

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Betchov's model¹ of quadratic turbulence consists of a large set of variables $\{x_k(t) \mid k=1,2,\dots,N\}$ obeying the following ODE's:

$$\frac{dx_k}{dt} = \sum_{m,n=1}^N M_{kmn} x_m x_n \quad k=1,2,\dots,N$$

The variable-coupling coefficients M_{kmn} are generated at random with some restrictions chosen to mimic the Fourier-decomposed Navier-Stokes equations.

The Betchov system is particularly attractive because the DIA has been solved for it and results can be compared with that solution. The research presented compares the DIA with the decimated amplitude scheme devised by R. Kraichnan.² This scheme generates the statistical properties of a large set of coupled ODE's with a small sample set of ODE's driven by a stochastic forcing.

A straightforward decimation of the Betchov system³ failed to reproduce certain statistical properties of the full system, most especially the decay time of the autocorrelation function. This lead to investigations which revealed the importance of the number of couplings associated with each variable. Because the couplings are generated at random, there are fluctuations in numbers of couplings per variable; these fluctuations are important and must be taken into account when adding stochastic forcing terms to the sample-set ODE's.

However, these fluctuations are peculiar to the random nature of the Betchov model and are not relevant to the decimation of Navier-Stokes Fourier mode equations, which is the long-term goal of this research.

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**Relativistic Considerations for
Electron Cyclotron Current Drive in Tokamaks***

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Electron trapping and modification of particle orbits by a toroidal magnetic trap have been predicted theoretically to be a problem for electron cyclotron current drive in tokamaks resulting in reduction in efficiency. The problem may be alleviated somewhat by having the wave power deposited on the strong magnetic field side of a flux surface based on non-relativistic arguments. However, relativistic considerations may change the physics both quantitatively and qualitatively. Four distinct situations can be identified depending on whether the wave is absorbed at the inboard or outboard side of a resonance layer and whether the resonance intersects the peak or the trough of the magnetic well. The efficiency for each case is estimated and experimental realization of these situations will be discussed.

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SIMULATION OF ANOMALOUS TRANSPORT IN JET

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Accurate measurements of the electron density profile in the JET experiment have enabled application of the η_e transport model (1). Good agreement with the experimental temperature profile, both in magnitude and shape, is obtained for a variety of operational conditions, including Ohmic heating and RF heated discharges, and including a simulation of a sawtoothed $q = 10$ discharge.

Connections with the Ohkawa scaling are noted, and the relevance of this scaling to modern concepts such as L to H mode transition, and pellet injection, are explored.

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Linear theory of $m = 1$ tearing modes

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$m = 1$ tearing modes are believed to play a crucial role in the experimentally observed dynamo effect in reversed-pinches (RFP's). Nonlinear theories [Z. G. An, et al., in Plasma Physics and Controlled Nuclear Fusion Research, 1984 (IAEA, Vienna, 1985), Vol. II p.231; A. Bhattacharjee and E. Hameiri, Phys. Rev. Lett. 57, 206 (1986)] use the linear characteristics of $m = 1$ modes as an important ingredient. Since the original $m = 1$ theory uses the tokamak ordering $kr/m \ll 1$ [B. Coppi, et al., Sov. J. Plasma Phys. 2, 533 (1976)], we reformulate the problem for RFP's. We begin with the linearized resistive MHD equations and derive an exact set of equations for the perturbed quantities v_{1r} , b_{1r} , and b_{1z} . Subsidiary orderings in the resistivity η are then imposed. The role of the "constant - Ψ approximation" is clarified. Connections are established with the dispersion equations of Coppi, et al. (ibid) and Coppi, Greene and Johnson [Nucl. Fusion 6, 101 (1966)]. The dynamo field $\vec{\epsilon} = \langle \vec{v}_1 \times \vec{b}_1 \rangle$ is computed.

RECONNECTION IN THE ADIABATIC LIMIT*

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Reconnection in the limit of vanishing resistivity, η , has been studied by Hu,¹ Biskamp,² Petschek,³ Tajima⁴ and others using various models on time scales comparable to Alfvén time. We offer numerical evidence of a slow (i.e., in a scaling without waves) reconnection in the adiabatic limit ($\eta \rightarrow 0$) of a resistive plasma. This confirms the purely adiabatic finding of Grad, Hu, and Stevens.⁵ The reconnection occurs across a separatrix which bounds regions where the plasma is modeled by resistive Grad-Hogan equations. In the adiabatic limit, all dissipation lies within the separatrix surface. In a purely adiabatic solution, the behavior at the separatrix would have to be described by jump conditions derived from the conservation equations.⁵ By using resistive equations, we avoid discontinuity and simply treat the problem as the limit of resistive solutions for small η . We induce reconnection by imposing a sinusoidal oscillation in the boundary conditions for a doublet configuration. The solution of the equations is calculated using the 2-D alternating dimension algorithm of H. Grad.⁶

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FIELD ERROR REDUCTION AT THE POLOIDAL GAP IN A REVERSED FIELD PINCH*

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The conventional Reversed Field Pinch is surrounded by a toroidal conducting shell that provides wall stabilization for the plasma. Usually, this shell is made of aluminum or copper, and it must have an insulated poloidal gap to permit penetration of toroidal loop voltage to the plasma. Many magnetic field perturbations will induce toroidal shell currents with poloidal Fourier components having mode numbers $m \geq 1$. A butt-joint poloidal gap will mode convert all of these image currents into potentially damaging magnetic-field errors with large spectra of toroidal-mode numbers. Overlapping tapered gaps have been proposed and partially tested for reducing these field errors.^{1,2} The mathematical basis for minimizing the $m = 1, n = 0$ field errors for all frequencies using tapered gaps, is presented in this paper. The optimal overlapping tapered gap is at least as long as the minor diameter of the shell. Various taper shapes are presented.

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Nonlinear Relativistic Electron Orbits in the Presence of Intense ECH RF Fields*

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The nonlinear interaction of FEL-generated large amplitude ECH fields with energetic electrons can be described by a relativistic harmonic Hamiltonian with canonical guiding center variables. Assuming a monochromatic traveling RF wave structure we show that the orbits described by this Hamiltonian can be reduced exactly to quadrature with integrals of the elliptic type. For reasonable RF field sizes satisfying $\tilde{E}_{RF}/B_0 \ll 1$, $\tilde{B}_0$ the ambient magnetic field, the associated quartic equations can be solved analytically and the orbit behavior studied as a function of the relativistic resonance parameter, $R = (1/\omega)(\omega - N\Omega_{ec}/\gamma - k_{\parallel}v_{\parallel})$. For a wave propagating perpendicular to $\tilde{B}_0$ with ordinary wave polarization we find that for R of order $(E_{RF}/B_0)^{2/3}$ or smaller, strong periodic modulations of Larmor phase and radius are experienced with orbital frequency which scales as $(E_{RF}/B_0)^{2/3}$. These orbits are described and the effects of these modulations on the self-consistency of the RF field are examined to determine whether strong orbit driven phase locking of the RF wave can occur and cause major changes in the RF absorption process.

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RESOLUTION OF ANOMALOUS THERMAL TRANSPORT MODELS *

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Expressions for the anomalous thermal transport derived from theoretical principles are difficult to distinguish in practice because of the inherent uncertainty of experimental data. A numerical transport simulation of Ohmic discharges in TFTR¹ has used a model for the electron anomalous thermal transport that gives a good all round fit for a wide variety of discharges. The enforcement of the shape of the steady state profile of T_e or the parallel current density has been found to require consideration of the nonohmic part of the electron energy balance in some manner within the transport model itself. This complicates matters by changing the scaling of the energy confinement time relative to the explicit a^2/χ_e expression. Other profile-consistent diffusion coefficients, based on different instability driving mechanisms, are found to be difficult to distinguish in simulation, given experimental uncertainties of 10% on many parameters. The degree to which different models can be resolved based on transport simulation of series of actual discharges is discussed.

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NOVA 2: A KINETIC-MHD STABILITY CODE*

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For the present day tokamaks and future fusion reactors the energetic particles play an important role in determining the global MHD behavior. To study the effect of energetic particles on MHD instabilities, a kinetic-MHD stability code (NOVA 2) has been developed. A low frequency ($\omega < \omega_b$) drift kinetic model is employed to describe energetic particle dynamics and the MHD fluid model for the bulk plasma. A set of integro-differential eigenmode equations has been derived and is numerically solved by employing cubic B-spline finite element in ψ -direction and Fourier decomposition in the poloidal direction. NOVA 2 is an extension of the previously developed nonvariational MHD stability code (NOVA)¹ for computing stability of low- n ideal MHD modes in the toroidal geometry. Some numerical examples of the energetic particle driven toroidicity-induced shear Alfvén waves² and fishbone type internal kink modes³ will be presented.

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FUSION ALPHA PARTICLE LOSS DUE TO RIPPLE AND MHD MODES^{*}

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A Hamiltonian guiding center formalism¹ is used to investigate fusion alpha particle loss due to ripple, sawteeth, and resistive tearing modes. Both TFTR and CIT are examined. Thermal wall loading and best positions for diagnostic location are examined.

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Arbitrary Larmor Radius Calculation of the Interchange Instability

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We re-examine the low density interchange criterion for the $m = 1$ mode for axisymmetric systems with large Larmor radii, such as occur in Astron, Migma, symmetric mirror, etc. Realistic geometry is considered with the only expansion being in $\omega \sim \omega_k \ll \omega_{ci}$, where ω is the mode frequency, ω_k the ion cyclotron frequency. In the equilibrium orbit there are two constants of motion, energy and angular momentum, and a third adiabatic invariant derived from the rapid radial motion. Starting from the Vlasov equation, and using Hamiltonian perturbation methods, we rigorously show that the plasma response function is nearly system independent, as has been observed in finite Larmor radius theory.¹ However, a new prediction, more optimistic than earlier work, is found for the low density threshold, for systems like Migma, that are disc-shaped, i.e., the axial extent Δz , less than the radial extent, r_p . The stability criterion is

$$\frac{a_h^2}{RR_c} > \frac{8n_h}{n_{i0} [1 + 2Z\omega_{ci}^2/\omega_{pi}^2]}$$

where ω_{pi}^2 is the mean ion plasma frequency, R_p the plasma radius, $RR_c \equiv$ radius time curvature radius which is roughly independent of space, a_h is the Larmor radius of the hot species n_h the density of the hot species, n_{i0} the ion density that can include a cold component, $Z \approx \frac{R_p + \Delta z}{\Delta z}$ (when $R_p > \Delta z$ we obtain the new stability result) and the bar denotes spatial average. Whereas, the older theory predicted instability at about the densities achieved in actual Migma experiments,² the present theory indicates that the experimental results were for plasmas with densities below the interchange threshold.

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**STABLE ACCESS TO SECOND STABILITY REGIME IN TOKAMAKS
USING RADIOFREQUENCY WAVES**

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In a recent calculation¹, we had suggested the use of radiofrequency waves for effective stabilization of ideal ballooning modes in a tokamak plasma. It was shown that for rather modest amplitudes of the rf field, a stable window to the second stability regime could also be created. The basic stabilizing mechanism is due to the nonresonant ponderomotive force produced by radial gradients in the rf energy which opposes the 'gravitational' forces due to bad curvature. Such a mechanism has proved effective in other situations e.g. in magnetic mirror experiments², where they have successfully suppressed Rayleigh-Taylor instabilities. With the availability of large RF power sources on Tokamak devices (e.g. for heating experiments), it appears feasible to attempt direct stable access to the high β regime by employing this scheme. In this paper, we provide a detailed calculation of the stability of the ideal ballooning modes in the presence of externally imposed rf waves near the lower hybrid frequency. Apart from the nonresonant ponderomotive contribution, we also take into account the sideband coupling contribution. At high rf power levels, there can be significant modifications in the equilibrium profile (e.g. distortion of the magnetic flux surfaces, change in Shafranov shift etc.). We study this effect through numerical and analytic solutions of the Grad-Shafranov equation in the presence of rf sources. We also discuss the rf power deposition profiles in the plasma and the feasibility of controlling them for the stabilization experiments.

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LOW FREQUENCY AXISYMMETRIC STABILITY OF ELONGATED TOKAMAKS*

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Elongated cross section tokamaks must be stabilized with respect to axisymmetric modes by nearby passive conductors and an active feedback system consisting of flux loop sensors, amplifiers, and current carrying feedback coils. We consider here the stability of axisymmetric modes with growth times long compared to the resistive time of the passive plates, but short compared to the resistive skin time of the plasma. The passive plates have no effect on these modes, but the plasma can still be treated using ideal MHD.

Using an analytic model, we show that the form of the eigenmode will in general depend on the placement of the flux loop sensors, and on the location of the feedback coils. Some placements will result in an unstable system for all values of the gain of the amplifier.

Using the simulation code TSC, we demonstrate how the low frequency axisymmetric stability of PBX is affected by the flux loop sensor locations. The results of these simulations are interpreted using Bode Diagram and Nyquist techniques, which aid in identifying unstable regions.

Finally, we discuss the formulation of a modification to the PEST code, which enables it to calculate the axisymmetric stability of a combined plasma, active feedback system.

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The Use of CO₂ or Millimeter Radiation for the Detection of α -Particles in a Fusion Plasma

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We examine the possibilities of detecting fusion alphas by either CO₂ or gyrotron radiation.

For coherent CO₂ scattering¹, $\omega_{inc} \gg \Omega_e, \omega_{pe}$ so that the Maxwellian plasma can be treated nonrelativistically in the longitudinal approximation. The scattering function is calculated for the slow-down alpha distribution and the optimal forward scattering angle is the smallest ($\theta \approx 0.5^\circ$) that the experimenter can handle. The lower hybrid resonance is quite sharp, and so may be difficult to resolve with GHz bandwidth receivers.

For coherent millimeter scattering², there are penetration problems as $\omega_{inc} \approx \Omega_e$ or a low harmonic, but large angle scattering (even $\theta > \pi/2$) is admissible. However, in the calculation of the scattering function relativistic effects are important and the longitudinal approximation is no longer valid. Preliminary results will be presented.

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Full-Wave and Fokker Planck Studies of ICRF Plasma Heating*

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We present a full-wave analysis of ICRF plasma heating in a general 1-D non-uniform equilibrium configuration. The theoretical analysis results in a pair of coupled second order differential equations for the ICRF electromagnetic field including the effects of strong wave damping and linear mode conversion. Numerical solutions are obtained assuming JET equilibrium parameters. For low field launch, our results indicate that, in this tokamak, heating in the fundamental minority frequency regime is dominated by nearly complete absorption of the fast wave energy by the various plasma species at moderate values of the parallel wavenumber. At lower values of this parameter, the majority of the incident wave energy is reflected towards the launcher. Direct electron absorption remains modest over the entire wave spectrum.

To understand the problem of electron heating in JET, we have developed a quasi-linear/Fokker-Planck model of the heating process. Our results indicate that the absorption of the ICRF wave energy leads to the rapid (a few milliseconds) development of energetic tail particles in the distribution function of the minority species. The energy of these particles is slowed down and transferred to the electrons via Coulomb collisions. We have seen that, for JET parameters, the absorption of 2 MW of ICRF power inside the $q=1$ surface leads to a 1 keV rise of the electron temperature over a time scale equal to 150 ms. These values agree well with those experimentally observed in JET.

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THEORY OF CLUMP-WAVE INTERACTIONS IN TRAPPED-ION-DRIVEN TURBULENCE

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As present and future-generation toroidal fusion experimental devices approach the very low collisionality regime (i.e., $\nu_{*e} \ll 1$, $\nu_{*i} < 1$), a particularly potent member of the η_i -driven family of instabilities is induced by trapped ions. This instability¹, which is triggered by unfavorable trapped-ion drift ($\omega_d > 0$) resonances, has a threshold ($\eta_{i,cr} \simeq 2/3$) that is lower than the conventional collisionless curvature-driven trapped-ion mode ($\eta_{i,cr} \simeq 3/2$). These modes, and the turbulence that may be expected to evolve from them, thus garner concern for any future CIT configuration, and as such, merit prior attention.

In an earlier study, Tagger and Pellat² explored the nonlinear saturation of the mode due to coherent trapping of the resonant particles in the electrostatic potential of the wave. Here, we investigate the same problem from the perspective of *turbulent* trapping and seek a steady-state situation regulated by interactions between an incoherent noise source determined by trapped ion phase space density granulations, and a coherent dissipation mechanism through collisions with electrons. Using a two-point renormalized theory, the manner in which both the instability and dissipation mechanisms determine the broadening of the spectral lines, is elucidated. The potential implications of the theory for confinement scaling are discussed.

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SHERWOOD THEORY MEETING 1987

Electron Neoclassical Heat Conduction in Tokamaks Performed by the Ions

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It has been shown¹ that ion-electron energy-scattering collisions produce an enhancement in the neoclassical ion heat conduction q_i , which for $T_e \gtrsim T_i$ is a higher order correction. But the most important property of this component of q_i was overlooked; namely, it acts like electron heat conduction. This is because heat is taken from, and given back to, the electrons at each diffusion step length (ρ_{i0}). The heat conduction is driven by the collision term $C_{ie}(f_{i1})$ and by $\partial C_{ie}(f_{i0})/\partial r$. The former was treated in Ref. 1; physically, because of f_{i1} the ions with $v_{\parallel} > 0$ have effectively a temperature greater than T_i , those with $v_{\parallel} < 0$ a lower temperature. In the steady state, the upward flow in energy caused by $C_{ie}(f_{i1})$ for $v_{\parallel} < 0$, and downward flow for $v_{\parallel} > 0$ must be balanced by a flow in pitch angle in the positive $v_{\parallel}$ -direction for high energies, in the negative $v_{\parallel}$ -direction for low energies. High energy ions entering the trapped region perform a banana orbit and become passing ions with $v_{\parallel} < 0$ at $r + \delta r$, where $\delta r = 2mhv_{\parallel}/eB_0$; there, energy is given back to the electrons via $C_{ie}(f_{i1})$. Low energy ions perform a smaller banana orbit inwards and carry less energy. The energy is given back to the electrons for the last time in the loss-cone region near the wall where there are no trapped ions with $v_{\parallel} < 0$.

This "effective" electron heat conduction is typically an order of magnitude larger than the normal neoclassical electron heat conduction. The part driven by $\partial C_{ie}(f_{i0})/\partial r$ is an example of a more general and important discovery: any ion heating mechanism which has a negative radial gradient will cause an enhancement in q_i . (Experimentally, centralized auxiliary heating has been observed to lead to poorer containment.)

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Transport Simulations of Ohmic Pellet Experiments at TFTR, ASDEX and ALCATOR-C*

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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[3] 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. Initial studies of TFTR pellet-fuelled experiments[2,3] were consistent with suppression of η_i -driven ion transport and improved confinement during the peaked profile phase following pellet injection.

Tests of the microinstability-based models have been extended to experiments on ASDEX and ALCATOR-C. It is found that the TFTR calibration of the model gives continued reasonable agreement (within 20%) with measured temperature profiles and confinement times for both gas and pellet-fuelled ohmic discharges on these machines.

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Questions and Issues on Parallel Processing I*

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Two of the four mainframes at the National MFE Computer Center are multiprocessor computers with vector hardware - a Cray-2 and a Cray-XMP/22. Members of the NMFECC Computational Physics Group will be available to answer questions and discuss issues pertaining to parallel processing.

*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.

Questions and Issues on Parallel Processing II*

Computational Physics Group
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Two of the four mainframes at the National MFE Computer Center are multiprocessor computers with vector hardware - a Cray-2 and a Cray-XMP/22. Members of the NMFECC Computational Physics Group will be available to answer questions and discuss issues pertaining to parallel processing.

*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.

EIGENVALUES ASSOCIATED WITH RELAXED STATES OF TOROIDAL PLASMA

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In the theory of relaxed states of toroidal plasmas /1/ certain eigenvalues of the Equation $\nabla \times \underline{B} = \mu \underline{B}$ play a crucial role. These eigenvalues are associated with vanishing toroidal flux and determine the onset of current saturation in a toroidal discharge. In axisymmetric systems there are both periodic and axisymmetric eigenfunctions and it is important to know whether the lowest eigen mode is periodic or axisymmetric. This depends on the shape of the poloidal cross-section and determines the nature of the current limited discharge.

We have computed the eigenvalues of periodic and axisymmetric modes in rectangular and elliptical cross-sections and in re-entrant Multipinch /2/ like cross sections. The re-entrant case required new numerical techniques. We find that in rectangular and elliptic cross-sections the lowest mode is always periodic. However in the Multipinch a transition occurs in which the lowest eigenmode changes from periodic to axisymmetric as the "waist" in the cross-section is made narrower. The critical width is determined. In the Multipinch the waist is below the critical width so we expect the current saturated discharge to be axisymmetric - unlike other pinch experiments where it is periodic. The properties of this symmetric state are known to be in good agreement with experimental observations /2/.

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THEORY OF $m^0=1$ MODES IN
REGIMES OF LONG MEAN FREE PATH RELEVANT TO IGNITING PLASMAS^{*}

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In the high temperature regimes characteristic of igniting fusion plasmas, the condition $(k_{\parallel} \lambda_{\text{mfp}})^2 < 1$ (i.e. the parallel wave vector $k_{\parallel}$ of $m^0=1$ modes has to be less than the inverse of the collisional mean free path λ_{mfp} over the whole inner layer) breaks down. A fluid model for the plasma dynamics inside the inner layer around the $q=1$ surface is then no longer appropriate. When a kinetic model is considered, we see that, for the electron component, the effects due to collisions have to be retained in the relevant kinetic equation (through a model collision operator), while the ion component can be taken as collisionless but with a finite Larmor radius. Following Ref. 1 to obtain a finite Larmor radius ion response, we have reduced the inner layer $m^0=1$ mode equations to a single, second order, inhomogeneous differential equation in the χ variable of Ref. 2 ($\chi = x dJ/dx$, with J the parallel current). We present results from a numerical solution of this mode equation in the case of ideal marginal stability, along with a comparison of these results with those obtained using a fluid model for the electron component.

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α -PARTICLE DISTRIBUTION IN IGNITION PLASMAS*

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As a first step in a systematic treatment of the transport and stability of ignition plasmas, we have analyzed the α -particle distribution from the Fokker-Planck equation. A new feature of our result is that after the slow-down time, the distribution of the α -particles in the thermal range is related to the continuous spectrum of the Fokker-Planck equation. The result also shows that even long after the slow-down time the α -particles will not assume a Maxwellian distribution at a temperature higher than the background ion temperature. As long as the total number density of the α 's produced in the plasma is small in comparison with the background ions, the α -particles will always have a step-function like slow-down distribution for velocity, a Maxwellian at the background ion temperature and a continuous spectrum contribution in the thermal range where $v \sim v_i$, v_i being the ion thermal velocity.

The present result can be described as follows. For $t \leq \tau_{SD}$, τ_{SD} being the slowing-down time,

$$f = \frac{I\tau_S}{4\pi} \frac{1}{v^3 + v_c^3} \equiv f_*, \quad v_* \leq v \leq v$$

and f vanishes otherwise, where v_0 is the 3.5 Mev velocity, I the α -production rate, v_c the critical velocity and v_* is a decreasing function in t , going to zero at the $t = \tau_{SD}$.

For $t > \tau_{SD}$, $f = f_*$ again for $v_i \ll v \leq v_0$. But for $v \sim v_i$, we find that

$$f = I(t - \tau_{SD})f_0 + f_1$$

where f_0 is a Maxwellian distribution at background ion temperature and f_1 can be expressed in terms of a known function $\alpha(\lambda)$ and the continuous spectrum eigenfunctions $f_\lambda(v)$ of the Fokker-Planck equation as

$$f_1 = I \int_{-\infty}^0 \alpha(\lambda)(1 - e^{\lambda t}) f_\lambda(v) d\lambda.$$

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Abstract Submitted for the 1987
Sherwood Theory Conference

Nonlinear Simulations of Radiative Condensation and Reconnection Instabilities,* G. VAN HOVEN, L. SPARKS and T. TACHI, University of California, Irvine, and D. D. SCHNACK, Science Applications International Corp., San Diego. -- Radiative instability arises when the optically-thin emission of an impure plasma falls with temperature, and the competing effects of parallel thermal conduction are inhibited by the magnetic structure. Under some conditions this plasma cooling instability can be very fast. We describe two non-linear manifestations of such energy-transport effects. One involves the filamentation of an ideal compressible plasma, as it responds to the pressure drop brought about by the large localized cooling. The second process, in which Coulomb resistivity ($\eta \propto T^{-3/2}$) is added to the description, leads to accelerated magnetic tearing.

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EFFECTS OF FAST ION SOURCES ON LOWER HYBRID CURRENT DRIVE*

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For lower hybrid current drive, the wave spectrum must be broad in order to achieve high current drive efficiency and also couple to a significant portion of a Maxwellian distribution.¹ A distortion of the electron distribution function away from a Maxwellian is produced when fast ions from a neutral beam source or fusion reactions slow down by collisions with electrons.^{2,3} This distortion can provide more electrons that interact with waves that have a lower parallel refractive index, and enhance the lower hybrid coupling to electrons. Enhancement of the current drive efficiency ($n_e RI/P$) has been observed experimentally in the JT-60 device.⁴

The effects of the electron distribution distortion caused by fast ions and current drive will be explored using a Fokker-Planck code for homogeneous magnetic fields. The ion distribution is determined using high energy sources and various simple transport models of the form νf , which give reasonable confinement times and ion source powers. The collision operator for determining the electron distribution is then calculated from the fixed background ion distribution using the Rosenbluth potentials.

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An Analytic, Large Aspect Ratio, High Beta Equilibrium*

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An interesting family of analytic solutions of the large-aspect-ratio limit of the Grad-Shafranov equation has been found. Their outer boundary is circular. The value of beta can be varied without limit, while keeping the safety factor profile nearly invariant. Thus it can produce a very close approximation to a flux conserving sequence of equilibria. Since it is an exact solution of the limiting equations, it is very far from the shifted-circle approximation for the magnetic surfaces that is often used to model such equilibria. In the limit of very large beta, the plasma current increases as the square root of beta, while the ellipticity of the flux surfaces near the magnetic axis increases as the fourth root. There is little or no reversal of the plasma current, even for very large values of beta.

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SHAPE OPTIMISATION OF LOW-ASPECT RATIO TOKAMAKS*

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Low aspect ratio improvements in stability are predicted by the ideal MHD model for pressure limits in tokamaks. We have conducted a series of calculations to estimate the increase in β_{crit} predicted by this model for various shaped configurations at aspect ratios below that of currently operating tokamaks.

The optimisation of Dee configurations at $A = 1.67$ has been studied with the RSTEQ/Balloon system and with the PEST codes. We find that pressure-driven modes are suppressed, as expected, for a moderately Dee-shaped plasma. (Shaping at low aspect ratio is affected by the tendency toward some elongation without explicit external coils). In comparison with reported optimisations at $A=2.5$, we find a factor 2-3 increase in the expected β_{crit} for $A = 1.67$.

The infinite-n ballooning stability limits of Dee, bean and crescent configurations have been compared for $1.67 \leq A \leq 2.5$ with the MOMCON fixed boundary moments equilibrium and the Balloon code. We find that, for the parametrization adopted, the ∞ -n stability improvements reported for strongly-shaped configurations at higher aspect ratio persist in the low aspect ratio regime.

In addition to using the kink-optimised profiles suggested by the Lausanne group, which have relatively high central q (~ 1.6), we made a limited study of pressure profile optimisation. The results suggest that similar aspect ratio-related increases in β_{crit} can be obtained for $q(0) \sim 1$.

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Inelastic Drift Wave Soliton Collisions and Transport*

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Coherent vortex structures¹ appear to be an important component of drift wave turbulence and the associated transport of particles and energy trapped for many rotations $\Omega_R = c k_v^2 \phi_{\max}/B$ in these structures $r_0 = 1/k_v$ may add significantly to the net transport flux. We study the inelastic collisions of the vortices looking for the conditions of radial displacements of the vortices. Using D and M for dipole and monopole, an example is the collision $D(r_0, u = +2) + D(r_0, u = -1) \Rightarrow M(r_0, u \simeq 0) + D(r_0, u = -1) + \text{waves}$ where the final dipole is displaced by $\Delta x \simeq r_0$ off the magnetic surface. The transformations between waves and vortices in the dissipationless, time reversible system is studied theoretically and through numerical solutions with a $(256)^2$ spectral code using a high order time integrator. The effects of sheared flows and the tilting instability on the vortices are also discussed. We discuss which effects of these results may generalize to electromagnetic vortices.²

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SCATTERING OF LOWER HYBRID WAVES IN TWO DIMENSIONS

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The present work represents an extension of our previous studies of lower hybrid wave scattering from random density fluctuations in one dimension^{1,2}. In our earlier work we were able to recast the boundary value problem describing the random wave potential into an initial value problem for the complex valued reflection coefficient R via a Riccati transformation and then use Monte Carlo simulations to obtain $\langle |R|^2 \rangle$, the mean reflected power. Here, we present initial results from the formulation of the same problem in two dimensions. We assume a cylinder with a finite antenna extent. We choose to solve this problem numerically using a finite element approach. The fluctuations are included in a concentric annulus representing an "edge" region. Results to date for the scattering pattern, reflection coefficient as a function of scattering thickness and amplitude will be shown.

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Numerical Simulation of Current Drive by Intense Microwave Pulses *

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Nonlinear particle dynamics can limit the power absorbed by Electron Cyclotron Resonance Heating (ECRH) for intense microwave pulses. This effect is quantified in Ref. 1 where it is also noted that gradients of $\mathbf{B}$ along $\mathbf{B}$ can enhance the energy absorbed of particles moving in one direction over that of particles moving in the opposite direction. Specifically, particles moving to larger B values can continue to have a resonant interaction with the wave because the cyclotron frequency can remain approximately constant; the increase in B is just balanced by the relativistic mass increase. Such particles can be described as being trapped in a rising phase-space bucket. For particles moving in the opposite direction, the decreasing value of B causes the heated particles to become nonresonant more quickly. This breaking of the symmetry of the heating can lead to current drive.

We investigate this current drive scheme numerically using the test particle code MCPAT which solves the guiding-center equations of motion. The effect of collisions and magnetic trapping after the pulse is switched off is studied by using the Green's function of Ref. 2 in conjunction with initial and final particle positions from MCPAT to construct the current-drive efficiency. Comparison will be given between the efficiency obtained numerically and that estimated in Ref. 1 which neglects trapped particle effects. We also compare with an analytic calculation of the idealized case where particles receive the maximum possible bucket lift. The role of $k_{\parallel}$ in enhancing the current-drive efficiency is investigated. An example will be given for the MTX experiment.

* Performed by LLNL for USDoE under Contr. W-7405-ENG-48.

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MAGNETIC PLASMA SURFACE WAVE INSTABILITIES

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Recent interest has arisen in the subject of electron inertial magnetic surface wave instabilities.¹⁻³ This type of instability is considered important in the understanding of spontaneous megaGauss magnetic field generation in laser produced plasmas. Observed transport phenomena in ICF experiments, e.g., surface energy transport, flux limitation, and anomalously fast plasma blowoff, have been attributed to magnetic field generation. Previous treatments of magnetic surface wave instabilities solve similar second order equations for the perturbed magnetic field but different conclusions are reached. These differences result from the equilibrium modeling used. Moreover, it is found that in all previous treatments the equilibrium modeling used in the sharp transition region is not consistent. A more careful choice for the equilibrium density and magnetic profiles is considered. In the transition region the model equation is significantly altered and this leads to a modified dispersion relation. Analysis of the dispersion relation is presented and the possibility of temperature gradient and acceleration induced instability is addressed.

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ION HEAT CONDUCTIVITY AND BOOTSTRAP CURRENT IN LOW-ASPECT-RATIO TOKAMAKS*

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Using DKES, the numerical method for solving a drift-kinetic equation for tori with arbitrary geometry,¹ we have examined neoclassical transport and bootstrap current in a variety of low-aspect-ratio tokamaks. Using these results, we are able to obtain an empirical expression for both which depends on collisionality, beta, aspect ratio, and a geometry factor (which depends on exact shaping, but otherwise varies only slightly from bean to crescent to D-shape plasma). In addition, bootstrap current is compared with a recently-derived expression derived by Hirshman. Results are consistent with earlier work^{2, 3, 4} and are applicable to STX,⁵ JET, and CIT.

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PROFILE CONSISTENCY AND TRANSPORT MODELLING*

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It is well established experimentally that the electron temperature profile in toroidal devices is relatively independent of the spatial deposition of auxiliary power and assumes a shape that can be related via neoclassical resistivity to that of a canonical, nearly Gaussian, current density profile outside the region of sawtooth activity. Furthermore, the fast propagation of the heat pulse associated with a sawtooth crash and the very rapid readjustment of the profile distortion caused by pellet injection both imply that a strong profile conserving mechanism (or mechanisms) is present in tokamak discharges. In this work, we use a modification of the BALDUR transport code to numerically investigate a semi-empirical transport model in which it is assumed that the cross-field electron heat flux is the result of at least two different, source-independent, transport processes described as fast and slow.^{1,2} The slow flux is taken to be Coppi-Mazzucato diffusion modified by a β_p correction for auxiliary heating. Several versions of the fast flux are examined, including one which is non-linear in the temperature gradient and one which combines enhanced diffusion and a heat pinch.² The effects of different forms of the edge boundary condition are also investigated.

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

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MHD SIMULATION OF DENSITY LIMIT DISRUPTIONS IN TOKAMAKS

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MHD simulations of density limit disruptions have been completed which reproduce some of the key observational features of experiments. The evolution of the discharge is simulated using the reduced MHD equations with a self-consistent evolution equation for the electron temperature. A radiative loss term ($\sim n^2$) has been incorporated into the electron temperature equation. When the density and radiation rate are increased, the plasma detaches from the edge as the total ohmic heating power is radiated rather than conducted to the boundary. As the temperature profile shrinks, the current flowing in the periphery is pushed inward and appears as a very strong skin current. During the large sawtooth crash resulting from these skin currents, a large bubble of cold plasma is injected into the center of the column. The q profile following this crash has a large value at the magnetic axis (up to 20), falls down to one, and then increases toward the boundary in a normal fashion. The $m/n = 2/1$ tearing mode, which is normally near marginal stability in a sawtoothed discharge with $q(0) \sim 1$, is strongly unstable in this bubble profile and grows until it encompasses the entire central plasma, fattening and broadening the current profile and throwing the thermal energy to the wall. This simulation resolves the longstanding contradiction between theory and experiment — the experimentalists see both $m = 1$ and $m = 2$ modes during the disruption^{1,2} while theoretically the $m = 2$ mode is always small in a sawtoothed discharge.

Work supported by U.S. Department of Energy.

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The Effects of Rotation and Collisions On The Trapped Particle Mode In The Columbia Linear Machine*

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In the Columbia Linear Machine (CLM) a collisionless curvature driven trapped particle mode has been produced, identified and analyzed⁽¹⁾. However, the presence of a large nonuniform radial electric field indicates the possibility of a significant rotational drive for the mode. Most present trapped particle mode theories with rotational drive^(2,3) are not suitable for application to CLM, because of the presence of substantial ($\sim 20\%$) transit (loss) particles and highly nonuniform radial electric field. In our model, we include a Rosenbluth-Simon⁽⁴⁾ 'flute' like response due to the rotation in the standard trapped and passing particle responses. The response of the transit electrons is taken to be Boltzmann. The resulting radial differential equation has been solved numerically by a shooting code and the results indicate that the rotational drive can compete with the curvature drive.

The effects of weak Coulomb and neutral collisions on the same mode has also been studied. The Coulomb collisionality has been modelled by a Lorentz pitch angle scattering operator^(5,6) while the neutral collisionality has been modelled by a particle conserving Krook operator. The result is that electron collisionality yields small stabilizing contributions to the collisionless MHD mode, which scale more like v instead of $\sqrt{v}$,^(5,6) because of the dominance of neutral collisionality.

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SHERWOOD THEORY MEETING 1987

**Ion Temperature Gradient Driven Drift Waves:
Particle Simulation and Theory***

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The ion temperature gradient driven drift wave in a sheared magnetic field is analyzed using particle simulation of full dynamic ions and adiabatic electrons in slab geometry with a temperature and density gradient.¹ Simulation results for the linear frequencies and growth rates are compared with a shooting code result. The higher radial mode harmonics are fundamental to our theoretical description of the ion temperature gradient driven drift waves.² Scalings of the nonlinear saturation of electrostatic fluctuations with η_i and L_S/L_T are presented. It is found that large modification of the temperature profiles are prevalent for most of our simulations. Therefore, we compare the saturation levels from our particle simulation with a quasilinear plateau theory calculation.³

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

SHERWOOD THEORY MEETING 1987

**Gaussian Closure Code and Direct Spectral Code Comparison
for 2D, 2-Field Turbulent Relaxation***

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The continuity equation (including viscosity) and Ohm's law (including resistivity) are used to analyze the nonlinear turbulent relaxation of the parallel vector potential and electron density. A coupled set of nonlinear spectral equations for the magnetic and internal energies are derived using a gaussian closure code.¹ Comparisons are presented between a 2D numerical spectral solution of the fundamental equations and the closure equations. In particular, cases with non-normal statistical occurrences are focused on. For the case of viscosity dominated systems, the direct spectral code indicates the formation of intermittent current filaments which result in large values of kurtosis and skewness.² Previously, in a similar regime, closure code solutions have been investigated in the realm of Navier-Stokes turbulence.³ In this study we compared high resolution solutions of the direct spectral code and the closure code in terms of basic quantities such as energy decay rates, spectra, kurtosis, and skewness.

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

SHERWOOD THEORY MEETING 1987

**Impurity Radiation Effects on
Resistivity Gradient Driven Turbulence in the Edge Plasma***

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One of the dominant sources of anomalous transport in the edge is believed to be due to resistivity gradient driven turbulence.¹ Previous calculations have focused on the stabilizing limiter effects and the destabilizing impurity radiation effects.² Furthermore, if impurity gradients are included in the resistivity analysis, the turbulence is enhanced for edge peaked impurity profiles.³ The focus of this work is a self-consistent treatment of impurity radiation effects on the basic resistivity gradient driven turbulence. To this end, the coupled set of resistive magnetohydrodynamics equations are solved while incorporating impurity radiation terms as well as an impurity equation. Alterations of the linear rippling mode as well as the nonlinear saturation levels of electrostatic fluctuations and transport values are presented and compared with experiments.

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

Sherwood Theory Conference, April 6-8, 1987

EIKONAL THEORY OF LINEAR MODE CONVERSION IN 4-DIMENSIONAL PLASMA*

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Small amplitude waves in nonuniform plasmas are described by systems of Maxwell and kinetic equations. Standard geometric optics theory¹ reduces the order of the system, so that only *one* first order equation for the scalar amplitude of the wave need be solved, by integrating along the rays. The condition for this reducibility of the system is the *nondegeneracy* of the wave, i.e., the requirement that only one of the eigenvalues of the *unreduced* $N \times N$ dispersion matrix $\mathbf{D}(k, x)$ vanishes at a time. In plasma regions where two or more eigenvalues of $\mathbf{D}$ become small simultaneously, the conventional geometric optics expansion scheme becomes singular.² Such degenerate regions are associated with linear mode conversion, the problem having been studied extensively in the one-dimensional case.³

We develop a 4-dimensional theory of the mode conversion associated with pairwise near-degeneracies of $\mathbf{D}$. The method uses a modified eikonal approximation and allows us to reduce the problem in degenerate regions to the solution of two coupled PDE's in general geometry, in the sense that the reduced dispersion functions $D_a(k, x)$ and $D_b(k, x)$ of the two orthogonally polarized coupled modes a and b have spatial gradients $\partial D_a / \partial x^\mu$, $\partial D_b / \partial x^\mu$ which need not be parallel. The main result of the theory is the transmission ratio $\exp(-2\pi |\eta|^2 / |B|)$, where η is the coupling coefficient and B is the Poisson Bracket $\{D_a, D_b\} = (\partial D_a / \partial x^\mu)(\partial D_b / \partial k_\mu) - (\partial D_a / \partial k_\mu)(\partial D_b / \partial x^\mu)$. The generalization to weak dissipation and ray divergence will be included.

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Numerically Induced Stochasticity

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 Steven P. Auerbach, *Berkeley Research Associates*

The motion of a particle in a one-dimensional potential well is regular, and can be reduced to a quadrature. Nonetheless, when a numerical integration scheme is employed to compute the trajectory, stochastic behavior can result.

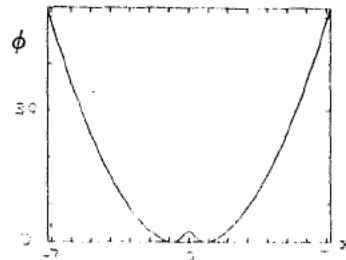
We consider simple integrators, such as the leapfrog mover, as *mappings* from (x,v) at one time level to (x,v) at the next. The leapfrog mover is:

$$v^{n+1/2} = v^{n-1/2} - \Delta t \nabla \phi(x^n); \quad x^{n+1} = x^n + \Delta t v^{n+1/2}.$$

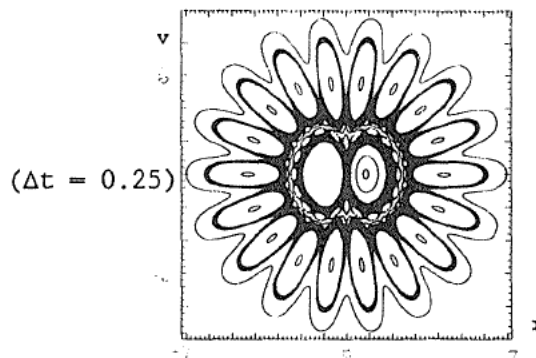
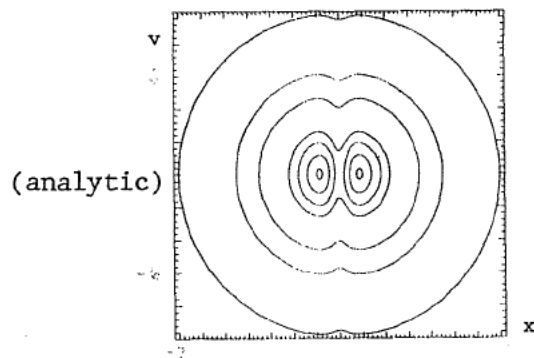
We linearly interpolate v to time level n , then plot the pair (x^n, v^n) . Our potential well is:

$$\phi(x) = x^2 + \frac{\alpha}{0.25+x^2}.$$

For $\alpha > 0.0625$, this well has a central "bump" but is harmonic at large x ; here we describe the case $\alpha = 1$. However, some chaos is evident even with $\alpha \leq 0.0625$ and no bump.



For small enough Δt (≤ 0.2), the stochastic behavior is limited to a small set of orbits which are (analytically) barely trapped in one sub-well, or are barely untrapped. There are in addition large trajectory errors (without stochasticity) for orbits which do not carefully sample the central bump. For larger Δt , a wide range of initial conditions yield a rich stochastic behavior, with a complicated island structure. These effects occur at timesteps well less than the classical leapfrog stability threshold for the harmonic part of the potential, $\Delta t_c = \sqrt{2} = (\text{period})/\pi$.



We have also observed similar behavior, in this potential and in $\phi = x^4$, using an implicit, time-centered mover which is stable for all Δt :

$$v^{n+1} = v^n - \Delta t/2 (\nabla \phi(x^{n+1}) + \nabla \phi(x^n)); \quad x^{n+1} = x^n + \Delta t/2 (v^{n+1} + v^n).$$

These results may be significant to (among other things) numerical studies of orbital stability and of the region of phase space accessible to an orbit. In a companion paper[†] we present a small- Δt analysis of the leapfrog mover.

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[†]Steven P. Auerbach and Alex Friedman, this meeting.

Long-Time Behavior of Numerically Computed Orbits: Small Time-Step Analysis

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A central problem in numerical simulation is understanding the relation between *exact* orbits and numerically computed orbits — *i.e.* between continuous dynamics and discrete dynamics. This problem is addressed numerically in a companion paper by Friedman and Auerbach[†], which presents results from one-dimensional orbit calculations using several integration schemes. Two qualitative results are apparent: (1) for small timestep, the numerical orbits lie on closed curves which are close to the exact orbits, even for a very large number of timesteps; (2) for large timestep the numerical orbits are chaotic. This paper describes an approach to understanding the small timestep behavior of the leapfrog algorithm. For small timestep Δ , a “pseudo-Hamiltonian” Ψ is constructed as a power series in Δ , by requiring that Ψ be conserved by the leapfrog algorithm. This requirement generates a sequence of partial differential equations. These equations may be solved by integrating along their characteristics, which are simply the exact orbits. The fact that these orbits are closed creates integrability conditions, which are shown to be satisfied by virtue of the fact that the leapfrog algorithm exactly conserves phase space area. Moreover, it is shown that the pseudo-Hamiltonian generates a synchronous “pseudo-dynamics”. That is, treating Ψ as the Hamiltonian for a continuous time system, and integrating the phase space flow forward from time t to $t + \Delta$, it is found that the continuous time motion reproduces the motion calculated by one step of the leapfrog algorithm. Thus, for small timestep, a continuous time Hamiltonian system has been constructed which is equivalent to the discrete time leapfrog algorithm. Since the pseudo-dynamical orbits are confined to curves of constant pseudo-Hamiltonian Ψ , and are “in synch” with the numerical orbits, this equivalence allows assesment of the accuracy of long-time integrations of numerical orbits (in one dimension) *via* the leapfrog algorithm.

* Work supported by the U.S. Department of Energy under contract W-7405-ENG-48

† Alex Friedman and Steven P. Auerbach, this meeting.

Sherwood Theory Conference, April 6-8, 1987

INTRINSIC ANGULAR MOMENTUM OF WAVES
AND THE TORQUE OF LINEAR MODE CONVERSION*

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Associated with the wave-oscillation of a particle, about its oscillation center, is an *angular momentum*, analogous to the gyromomentum of a guiding center. Thus one can attribute intrinsic angular momentum (or "spin") to a wave packet in a magnetized plasma. We derive an explicit expression for this spin, and note its crucial dependence on the wave polarization.

In linear mode conversion, wave action is transferred between two waves with orthogonal polarization. Hence, although wave action, energy, and momentum are conserved, we expect that wave spin is *not* conserved. We present our calculation of the resulting torque on the background plasma.

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DESTABILIZATION OF GLOBAL COMPRESSIONAL
ALFVEN MODES BY A HOT ALPHA PARTICLE SPECIES IN AN FRC

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In previous local calculations,¹ we have found that compressional Alfvén modes with $|\omega_{\alpha}^*/k_{\perp} v_A| > 1$ are destabilized by small fractions of alpha particle pressure. This condition may be re-expressed as

$$\frac{1}{4} \frac{m_i}{m_{\alpha}} \frac{T_{\alpha}}{(T_e + T_i)} \beta_{\text{Tot}} \rho_{\alpha}^2 / L_n^2 > 1 .$$

Here, β_{Tot} is the local background plasma beta. Since both the volume averaged beta and the Larmor radius of ions are large in planned FRC's, we expect this instability to be of interest in this type of reactor. Hence, we have completed, and will present the global stability analysis for these modes in a model FRC equilibrium.

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

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Relaxation of an Ablated Pellet Cloud
Using the Grad Transport Model*

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Experimental studies in tokamaks indicate that an injected pellet quickly ablates and spreads over flux surfaces. Here, we study the subsequent relaxation of the ablated pellet cloud numerically, using an alternating dimension code based on H. Grad's 3D transport formulation¹. To simulate the initial cloud we introduce a positive density perturbation counter balanced by a negative temperature perturbation to produce a zero perturbation in pressure. We can simulate the pellet cloud realistically in that it be spread over many flux surfaces so that the perturbations need not be local; moreover, the perturbation amplitudes can be large. For local pulses we find that the pellet disturbance excites mainly the slow diffusion eigenmode², λ_- ; the fast eigenmode, λ_+ , only slightly. Thus we expect the cloud to have a longer life than estimated from the thermal conductivity κ . This is in contrast to our earlier result on pure heat pulses, which mainly excite the λ_+ mode and, hence, diffuse faster than estimated by thermal conductivity.²

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*Work supported by U.S. Department of Energy, Grant No. DE-FG02-86ER53223.

Ion Microstability of a Tara Neutron Source

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A proof of principle experiment is being proposed¹ for a neutron source based on an axisymmetric tandem mirror. The device, which would be constructed from the existing Tara hardware, would consist of a central cell with a mirror ratio of 3 (made from one of the present Tara axicells), with neutral beams injected at an angle of 45° at the midplane, forming a hot sloshing ion distribution; on each side of the central cell there would be a straight section (made from the present Tara central cell) ending in a cusp which would provide MHD stability. A neutron source with this configuration has several advantages over a tokamak neutron source². We have determined the constraints put on this design by ion microstability, both for the proposed proof of principle experiment and for a full scale neutron source. We have considered both loss cone instabilities (DCLC) and anisotropy instabilities (AIC). At the high densities proposed ($n_i > 10^{13} \text{cm}^{-3}$), the DCLC mode can localize axially, so it is necessary to have at least 5-10% warm ions at every location. Assuming Boltzmann ions and electrons in the straight sections, we require that the ratio of density in the straight sections to peak hot ion density in the central cell should be at least $\sqrt{5} - 10\%$. More precise DCLC stability thresholds, including the effect of the loss cone in the warm ion distribution due to the finite mirror ratio of the cusp, have been obtained from the axial eigenmode code MSTARA. This code has recently been modified to reduce the effects of the "noisiness" which often plagues axial eigenmode codes for DCLC at high frequencies. Stability to the AIC mode requires β less than about 20%, which is not a serious constraint on the proposed proof of principle experiment, but is a constraint on a full scale neutron source.

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Multiquadric Interpolation of Numerical Tokamak Equilibria*

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We describe a novel interpolating algorithm¹ for the magnetic field $\mathbf{B}$ of a tokamak of non-circular cross section. We use multiquadric interpolation for the poloidal flux function $\psi(R, Z)$ computed by any of three different MHD equilibrium codes: NEQ, GAQ, and EFIT.^{2,3,4} All of the cited equilibrium codes output $\psi(R, Z)$ on a rectangular mesh, but the multiquadric algorithm works also for ψ -values given at a set of scattered points in the RZ -plane. The global nature of the algorithm is indicated by the form of the interpolant

$$\psi(R, Z) = \sum_{i=1}^N a_i b_i(R, Z),$$

where the a_i are found by solving a system of N linear equations, and the basis functions

$$b_i(R, Z) = [(R - R_i)^2 + (Z - Z_i)^2 + C^2]^{1/2},$$

with C a constant, are such that all N data points (R_i, Z_i) , not only those nearby, contribute to $\psi(R, Z)$. We find, typically, that we need to use only a small fraction, 1.8%, of the gridded data provided by the equilibrium codes to reduce errors in ψ to 1%. The system of linear equations is moderate in size, $N < 200$. For some applications, an advantage of the interpolant is that derivatives of any order are finite.

As an example of the use of multiquadric interpolation of ψ , we display results of electron-cyclotron ray-tracing calculations for the D III-D, CIT, and TIBER tokamaks.

* Work performed for the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48, and by Hunter College under contract DE-FG02-84-ER5-3187.

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A UNIFIED THEORY OF RIPPLE TRANSPORT IN STELLARATORS

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A series solution in k^2 of the bounce-averaged kinetic equation

$$\frac{\partial f}{\partial \theta} + r \frac{\partial F_M}{\partial r} = C(f)$$

is presented for ripple trapped particles in a stellarator. Here k^2 is a pitch angle variable, with ripple trapped particles satisfying $0 < k^2 < 1$. Unlike previous solutions which are asymptotically valid for particular orderings of the kinetic equation, this series solution is valid at all low collision frequencies for both "standard" stellarators and a class of "transport optimized" stellarators. The solution is obtained by assuming $f = (\partial F_M / \partial r)(X(k^2) \cos \theta + Y(k^2) \sin \theta)$ and by requiring the series solution to satisfy the boundary conditions, $\partial X / \partial k^2 (k^2 = 1) = -2\epsilon_h X(k^2 = 1) / \epsilon_t$ and $Y(k^2 = 1) = 0$, where ϵ_t and ϵ_h are the magnitudes of the toroidal and helical field ripples, respectively (these boundary conditions are altered slightly in the case of transport optimized stellarators). Diffusion coefficients obtained using this series solution show excellent agreement with those obtained numerically.

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Development of a microwave FEL code using waveguide modes.*

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A free electron laser code is being developed for application to the LLL tokamak current drive experiment. This single frequency code solves for the slowly varying complex field amplitude using the usual wiggler-averaged equations of existing codes, except that it describes the fields by a 2D expansion in the vacuum waveguide modes, instead of for example the 1D finite element method of the LLL code FRED¹, which has only limited 2D information. Thus the new code has 2D aspects such as the capability of following the TE_{0n} and TE_{m1} modes simultaneously, whereas FRED is limited to one or the other set. The TM_{mn} modes are also included. The waveguide expansion and coupling coefficients are those developed by Wurtele², which include spatial variations in the fields seen by the wiggler motion of the particles. Initial test versions (no taper, no space charge) with only a few modes produce results very similar to those achieved by FRED. Later versions will use the same waveguide expansion for a multifrequency code for application to sideband instabilities.

*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.

¹ Orzechowski et al, IEEE J. Quantum Electron.**21**, 831 (1985), and Phys. Rev. Lett.**57**, 2172 (1986).

² Wurtele, Phd Thesis UC Berkeley (1985), and Wurtele et al, Nucl. Instr. and Meth. **A250**, 176 (1986)

Suppression of External Kink Modes in Tokamaks by RF Ponderomotive Effects*

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In a recent paper¹ a generalized energy principle was derived which incorporates the nonlinear coupling of applied rf waves to MHD instabilities in a plasma. It was shown that the ponderomotive force exerted by an appropriate rf wave structure could stabilize high- n ballooning modes in a tokamak. This work is extended here to treat the stabilization of external kink modes by the near field of an antenna aligned parallel to B . For this antenna geometry, and in a frequency regime where no Alfvén resonance is present in the plasma, the rf wave structure is radially evanescent with a scale length of order several electron skin depths and contains a significant $E_{\parallel}$ component. Because of this rapid decay and the large parallel conductivity, even modest values of $E_{\parallel}$ can provide a substantial ponderomotive force at the plasma edge. The effect of this force is to make external kink perturbations energetically less favorable. A stability criterion will be given, and recent progress in numerical modeling of the appropriate near field structure will be reported.

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*Work supported by U.S.D.O.E. contract DE-AC03-76-ET53057.

The H-Mode, Counter-Injection, and Poloidal Rotation*

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Counter-perpendicular neutral beam injection in PDX limiter plasmas gave stored energy comparable to that obtained with co-injection, despite $\approx 50\%$ fast ion orbit losses. Recent A3DEX results indicate that the H-Mode is obtained at lower beam power with counter-injection than with co-injection. In all neutral beam injection experiments, improved particle confinement is observed with counter-injection, as in the H-Mode. Here we speculate on a possible connection between the H-Mode and counter-injection, through edge poloidal rotation driven by the loss of ion banana orbits across the plasma surface.

In neutral beam injection, initial fast ion orbits can have a different orbit-averaged mechanical toroidal angular momentum, $\langle mRv_\phi \rangle$, than the injected neutrals from which they originated. During the slowing-down process orbit effects (e.g. trapping and de-trapping) can also change the mechanical angular momentum of fast ions, without collisionally transferring all of the change in momentum to the plasma. The torque on the fast ion population which gives rise to these effects is due to the radial beam ion current crossed with the poloidal field, $j_{rb}B_\theta$. This torque is transferred to the bulk plasma via the net radial plasma current which is required for quasi-neutrality: $j_{rb} + j_{rp} = 0$. This effect can exert a much stronger *poloidal* than toroidal force on the plasma, by the ratio B_θ/B_p . Indeed for the poloidal rotation driven by this effect to be negligible compared to similarly driven toroidal rotation, in the radial force balance equation, requires the ratio of the poloidal to toroidal rotation damping times to obey $\tau_\theta/\tau_\phi \gg (B_\theta/B_p)^2$, which may not be the case in real tokamak plasmas. Heavy ion beam probe data from ISX-B indicate that the radial electric fields at the edge of counter-injected plasmas are greater than can be explained without substantial poloidal rotation. These rotation speeds are sufficient to drive a large inward neoclassical pinch, which would substantially increase τ_p .

In divertor plasmas, when $u_{*i}(a) < 1$ at the edge, losses of trapped bulk ions across the outermost flux surface result in a net $j_r B_\theta$ counter-toroidal torque on the plasma, equal and opposite to the co-toroidal torque on the divertor plates, due to the lost co-going ions. If we assume that the dominant ion loss is in the form of such banana orbits, the compensating radial current $I_r = N/\tau_p$, crossed with the toroidal field, should drive a strong poloidal rotation, comparable to the poloidal ion sound speed, and so a strong ion pinch in a region near the plasma surface of width $\approx$ one ion banana orbit. The resulting increased τ_p and reduced recycling allow the edge T_e to rise, and energy confinement to improve.

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Moses Roudel
MSF 642 - Hiroshima Workshop
LASL

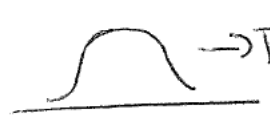
$$q_j = J_0 / \sigma$$

$$= \frac{5a^2 B}{R I} \frac{1}{q_0}$$

$$\downarrow$$

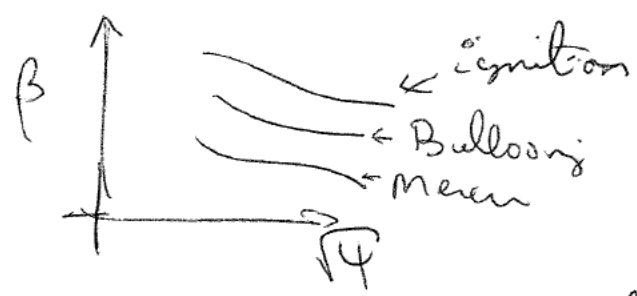
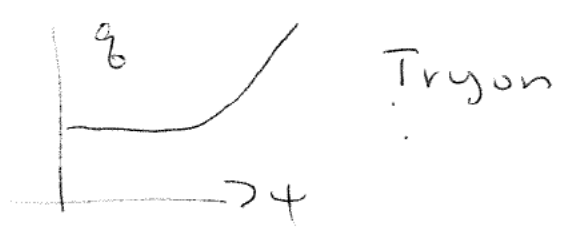
$$\frac{1 + \alpha_0^2}{2\alpha_0} q_0^{-1} \alpha$$

even $q_4 = 3$

 → Broad current Profile

$$\beta > 3I/aB$$

low shear
→ low ballooning limit



Ohmic constant profile
Ballooning limit before kink limit

Normalized current

$$I_N = I/aB$$

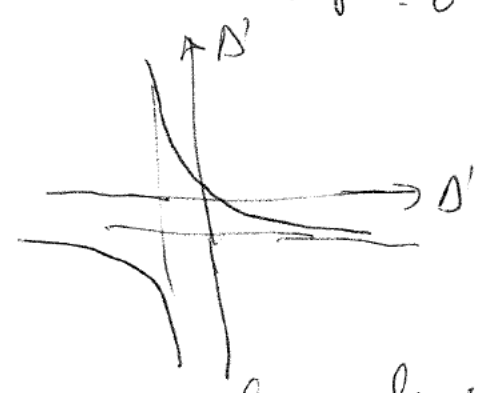
→ maximum I_N

β limited by I_N
then ballooning

Linear layer

$\Delta'_m(w)$ layer

$$(\Delta'_{m+1} - \alpha)(\Delta'_a - \beta) + \gamma = 0$$



Nonlinear layer
 $w > \delta$

$$\Delta'_m = \Delta'_m \left(\psi, \frac{d\psi}{dt} \right)$$

$$\text{Ruth.} \propto \frac{d}{dt} \psi_m^{1/2}$$

$$\left[I + \frac{E}{\omega} \cdot \Delta'(\psi_m, \dot{\psi}_m) \right]_4 = 0$$

$\alpha < 0, \beta < 0, \delta \beta > \delta$
stable
= no part of tynahh
in first quadrant

$$\left(\frac{1}{r \Delta'_1} - \frac{\epsilon^2 \delta W_1^T}{S_1^2} \right) (r_2 \Delta'_1 - \Delta'_2{}^c) + \frac{\epsilon_1^2 \delta W_{q2}}{S_1^2} = 0 \quad \sqrt{2} \text{ total coils}$$

$$S_1 = r \delta'_2 \quad \delta W_1^T = \text{Bussac et al}$$

$$\text{if } \alpha \sim \delta(\epsilon) \quad \sim \beta \quad \text{then need } \Delta_m^{1c} \Delta_{m+1}^{1c} > I^2$$

$$\sqrt{\delta} \sim \epsilon \quad () () - \epsilon^2 I^2 > 0 \quad \text{destabilizing}$$

$$(\Delta'_{m-\alpha})(\Delta'_{m+1-\beta}) - \delta = 0$$

Init. value curl α, β, δ

get $\delta(\omega)$

Invert large ϵ or

to get Δ'_m, Δ'_{m+1}

role ω at each sub

need then to match