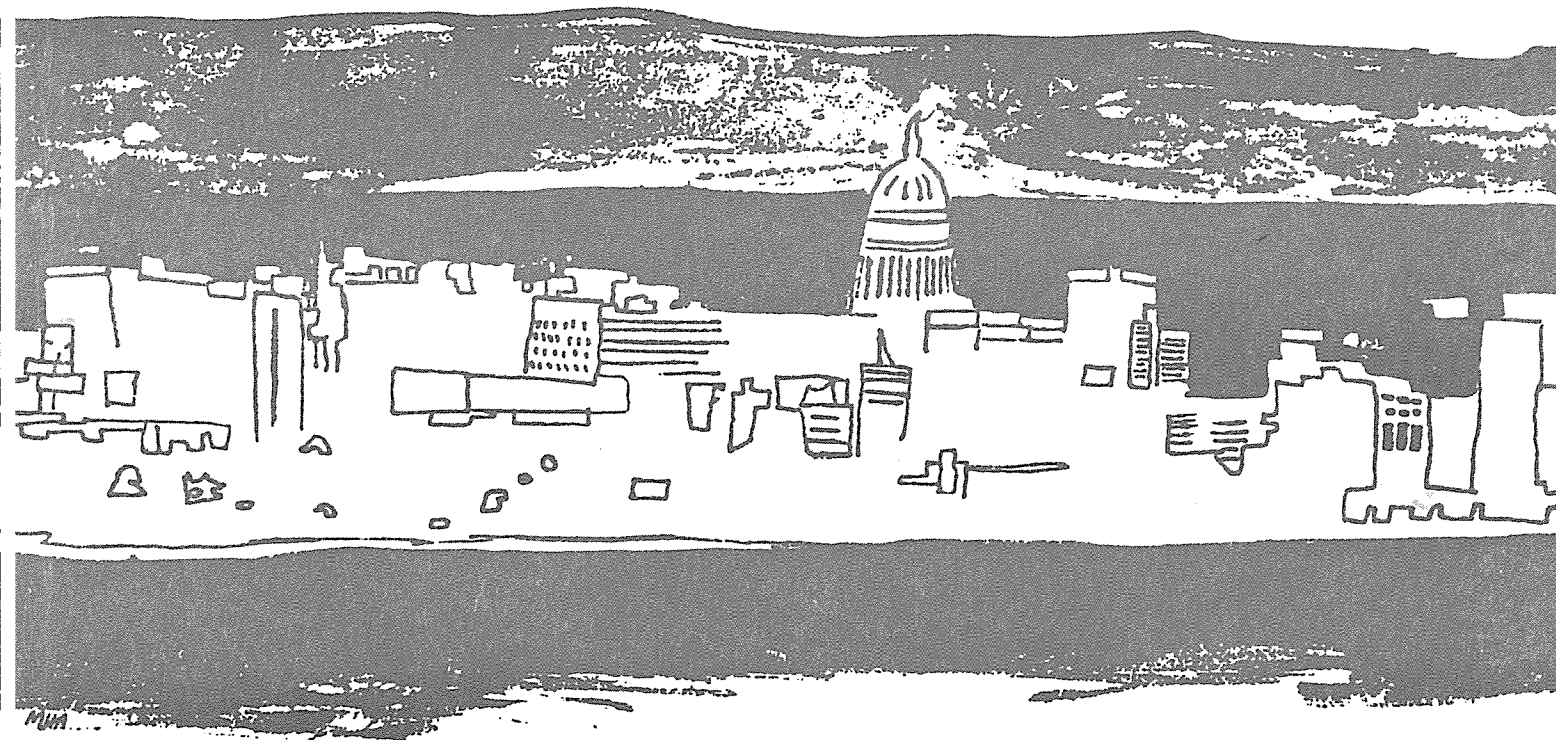


SHERWOOD

SHERWOOD, 1985

1985
SHERWOOD
THEORY CONFERENCE



ANNUAL
CONTROLLED FUSION THEORY
MEETING

APRIL 15-17, 1985
MADISON, WISCONSIN



CONTROLLED FUSION THEORY CONFERENCE

APRIL 15 - 17, 1985
MADISON, WISCONSIN

HOSTED BY

UNIVERSITY OF WISCONSIN
MADISON, WISCONSIN 53706

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**1985 SHERWOOD THEORY CONFERENCE SCHEDULE
THE WISCONSIN CENTER
APRIL 15 - 17, 1985**

Registration

April 14, 1985 - 6:00 PM - 10:00 PM
April 15 - 16, 1985 - 8:00 AM - 9:00 PM

Reception in the Alumni Lounge - Wisconsin Center
April 14 - 6:00 - 10:00 PM

ORAL AND POSTER SESSION SCHEDULE

**All Sessions will be in the Wisconsin Center except for those
indicated to be in the Memorial Union Theater**

Monday, April 15, 1985

WELCOME - 8:30 - 8:40 AM - (Memorial Union Theater)

1A - 8:40 - 9:30 (Review Paper - Memorial Union Theater)

1B - 9:40 - 10:10 AM (Oral Session) 1P - 9:40 - 10:55 AM (Poster Session)

1C - 10:30 - 12:15 (Oral Session) 1Q - 11:00 - 12:15 (Poster Session)

12:15 - 2:00 PM - Lunch

1D - 2:00 - 3:15 PM (Oral Session) 1R - 2:00 - 3:30 PM (Poster Session)

1E - 3:45 - 5:00 PM (Oral Session) 1S - 4:00 - 5:30 PM (Poster Session)

Tuesday, April 16, 1985

2A - 8:30 - 9:20 (Review Paper - Memorial Union Theater)

2B - 9:30 - 9:55 AM (Oral Session) 2P - 9:30 - 10:45 AM (Poster Session)

2C - 10:30 - 12:15 (Oral Session) 2Q - 11:00 - 12:15 (Poster Session)

12:15 - 7:30 PM (AFTERNOON FREE)

2D - 7:30 - 8:45 PM (Oral Session) 2R - 7:30 - 9:00 PM (Poster Session)

2E - 9:00 - 10:15 PM (Oral Session) 2S - 9:15 - 10:45 PM (Poster Session)

Wednesday, April 17, 1985

3A - 8:30 - 9:45 AM (Oral Session) 3P - 8:30 - 10:15 AM (Poster Session)

3B - 10:20 - 12:15 (Oral Session) 3Q - 10:30 - 12:15 (Poster Session)

**Coffee and Tea available - 9:45 AM - Noon - Monday and Wednesday
Coffee, Tea, Beer and Soda available - 2:00 - 5:30 PM - Monday
and 7:30 - 9:00 PM - Tuesday**

1985 SHERWOOD THEORY CONFERENCE
ANNUAL CONTROLLED FUSION THEORY CONFERENCE
APRIL 15-17, 1985

SUNDAY, APRIL 14, 1985

6:00 PM - 10:00 PM	REGISTRATION	Wisconsin Center
6:00 PM - 10:00 PM	RECEPTION	Wisconsin Center - Alumni Lounge

MONDAY, APRIL 15, 1985

8:00 AM - 9:00 AM	REGISTRATION	Wisconsin Center
8:30 AM - 8:35 AM	WELCOME (J. L. Shohet)	Memorial Union Theater

1A REVIEW SESSION 8:35 - 9:35 AM Memorial Union Theater (Chair: E. J. Caramana)

1A1. Lie Algebraic Methods for Computing Charged Particle Beam Transport. A. Dragt.

1B MIRRORS 9:45 - 12:15 Wisconsin Center - Lakeshore Room (Chair: T. B. Kaiser)

- 1B1. Plasma Response To Drift-Pump Fields In Tandem Mirrors. Y. J. Chen, D. E. Baldwin, J. A. Byers, R. H. Cohen, T. B. Kaiser, W. M. Nevins, L. D. Pearlstein, and H. Ramachandran.
- 1B2. Axisymmetric Mirror Plasma Stable To MHD and Alfvén Ion-Cyclotron Modes. G. R. Smith, H. L. Berk, and L. L. LoDestro.
- 1B3. On the Construction of Optimal 3-D MHD Equilibrium Configurations. M. P. Bernardin and J. A. Tataronis.
- 1B4. Stability of a Hot Electron Symmetric Tandem Mirror With Thermal Barrier. K. T. Tsang.
- 1B5. Oscillation Center Theory and Ponderomotive Stabilization of Mirrors. P. L. Similon.

1P POSTER SESSION 9:45 - 11:00 AM Wisconsin Center - Alumni Lounge and Robert P. Lee Lounge

- 1P1. Ballooning Stability Boundaries with Plasma Compression. D. J. Sigmar, W. A. Cooper, and S. P. Hirshman.
- 1P2. Coherent CO-2 Laser Scattering For Alpha Particle Detection. L. Vahala, G. Vahala, and D. Sigmar.
- 1P3. Analytic F-Theta Curves for Reversed Field Pinches. K. M. Ling and D. A. Baker.
- 1P4. Stability of An Axisymmetric Mirror With An Energetic Ion Component. J. F. Krall, C. E. Seyler, and R. N. Sudan.
- 1P5. Trapped Electron Effects On Electrical Conductivity and Runaway Production. M. G. McCoy, G. D. Kerbel, and R. W. Harvey.
- 1P6. Optimization of Neutral Beam Injection Into ATF. J. A. Rome and R. N. Morris.
- 1P7. 3 D Nonlinear MHD Simulation In Toroidal Geometry. W. Kerner, H. Welter, D. Biskamp, and D. S. Harned.
- 1P8. Wave-Induced Current and Heating In a Non-Homogeneous Plasma. Y. P. Pao.
- 1P9. Highly-Elongated Ideal Free-Boundary Magneto-hydrostatic Equilibria. H. St John, F. J. Helton, and R. W. Moore.
- 1P10. Singular Finite Element Methods For Finite Beta Plasmas. A. D. Miller and R. L. Dewar.
- 1P11. Energetic Electron Effect on MHD Modes In Tokamaks. J. Y. Hsu, M. S. Chu, J. S. Kim, and K. K. Lee.
- 1P12. Strong Damping of Electron Cyclotron Waves in Nearly Parallel Stratified Plasmas. D. B. Batchelor, A. Fruchtman, K. S. Riedel, and H. Weitzner.
- 1P13. Artificial Intelligence Methods For Facilitating Large-Scale Scientific Computations. N. T. Gladd and N. A. Krall.

- 1P14. Solution of the Electron's Fokker-Planck Equation for Tandem Mirror Trapped Particle Modes. H. L. Berk.
- 1P15. Ponderomotive Force Pumping of Tandem Mirror Thermal Barriers. J. F. Santarius and J. D. Callen.
- 1P16. Kinetic Theory of ICRF Stabilization of Interchange-Ballooning Modes. D. A. D'Ippolito and J. R. Myra.
- 1P17. Lower-Hybrid Current Drive In the Presence of an Ohmic Electric Field. V. Fuchs, M. M. Shoucri, A. Bers, and R. A. Cairns.
- 1P18. Fokker-Planck Calculations For JET ICRF Heating Scenarios. J. Scharer, J. Jacquinet, and P. Lallia.
- 1P19. Simulation of Plasma Relaxation. D. D. Schnack and D. C. Barnes.
- 1P20. Dynamo Model For the Reversed-Field Pinch In the Small Flow and Resistivity Limit. D. Dobrott, D. C. Barnes, and D. D. Schnack.
- 1P21. Alpha Particle Destabilization of Ballooning Modes In Tokamaks For Various Energy Distributions. D. A. Spong, D. J. Sigmar, D. E. Hastings, W. A. Cooper, and K. T. Tsang.
- 1P22. Half-Coalescence of the $m = 1$, $n = 1$ Magnetic Island: A More General Formulation. M. N. Bussac, R. Pellat, J. L. Soule, and M. Tagger.
- 1P23. Numerical Calculation of Neoclassical Ion Thermal Conductivity and Viscosity. S. K. Wong.
- 1P24. A New Three-Dimensional MHD Equilibrium Code. A. Reiman and H. Greenside.
- 1P25. Modified Convective Cells In Plasmas. D. Jovanovic, H. L. Pecselli, and J. J. Rasmussen.

1Q POSTER SESSION 11:05 - 12:20 Wisconsin Center - Alumni Lounge and Robert P. Lee Lounge

- 1Q1. Energy Transduction In Pellet-Injected Plasmas. F. J. Mayer.
- 1Q2. A Preliminary Examination of ICRF Heating Theory on ATF. R. J. Kashuba and D. E. Driemeyer.
- 1Q3. Numerical Solution of the Fokker-Planck Equation For Ripple Transport In Stellarators. W. N. G. Hitchon and H. E. Mynick.
- 1Q4. ICRF Wave Coupling Propagation and Heating In Large Tokamaks. H. Romero, N. T. Lam, and J. Scharer.
- 1Q5. Alpha-Particle Behavior In Stellarator Reactors. D. Ho and R. M. Kulsrud.
- 1Q6. Resistive Ballooning Modes in a High Temperature Plasma. J. W. Connor, R. J. Hastie, and T. J. Martin.
- 1Q7. Three-Dimensional Tandem Mirror Equilibria With Finite Larmor Radius Effects. L. D. Pearlstein and B. McNamara.
- 1Q8. Double Adiabatic Compression of Field-Reversed Configurations. R. L. Spencer.
- 1Q9. Inductive Inhibition of Cold-Plasma Stabilization of Mirror-Confined Plasmas. G. E. Guest, R. L. Miller, and M. Z. Caponi.
- 1Q10. Stability of Islands to Antisymmetric Perturbations in Tokamaks. A. Y. Aydemir.
- 1Q11. Application of Low Frequency Electromagnetic Variational Form To Trapped Particle Modes With Azimuthal Rotation. B. Lane and H. Berk.
- 1Q12. Toroidal Viscosity and Ambipolarity In the Neoclassical Theory of Axisymmetric Tori. P. J. Catto.
- 1Q13. Transport Code Simulations with a Comprehensive Drift-Ballooning Model. R. R. Dominguez, W. Pfeiffer, and R. E. Waltz.
- 1Q14. Axisymmetric Stability Studies of a Divertor Limited Bean-Shaped Tokamak. N. Pomphrey, S. C. Jardin, and M. Okabayashi.
- 1Q15. Comparison of Various Thermal Conduction Models On the Prediction of Density Limits In Tokamak Discharges. P. N. Guzdar and J. Q. Dong.
- 1Q16. Numerical Simulation of Transport In a Field Reversed Configuration; Comparison With Experiment. D. E. Shumaker.
- 1Q17. Modeling Ambipolar Potential Formation Due To ICRF Heating Effects On Electrons. J. W. Johnson, J. D. Callen, and N. Hershkowitz.
- 1Q18. The Spectrum of Resistive Viscous MHD. K. Riedel.
- 1Q19. Evolution Of A Tokamak Close To the Beta Limit. J. S. Kim, M. S. Chu, and J. K. Lee.
- 1Q20. Direct Implicit Particle Simulation of Tandem Mirror Transport. B. I. Cohen, M. E. Stewart, and C. K. Birdsall.
- 1Q21. High Frequency Modes In Toroidal Plasmas. P. Detragiache, B. Coppi, S. C. Cowley, R. M. Kulsrud, and F. Pegoraro.
- 1Q22. Ion-Viscosity Effects On $m = 1$ Modes. F. Porcelli and B. Coppi.

- 1Q23. The Computation of Single Helicity RFP Ohmic States. G. Marklin.
- 1Q24. A Magnetic and Inertial Hybrid Fusion. A. Hasegawa.
- 1Q25. Strong Interaction of Resonant Particles With Wavepackets. J. R. Cary.

1C MHD EQUILIBRIUM AND STABILITY 2:00 - 5:30 PM Wisconsin Center - Lakeshore Room (Chair: D. C. Barnes)

- 1C1. JET MHD. J. A. Wesson.
- 1C2. Toroidal Minimum-B Equilibria and Related Configurations. C. M. Bishop and J. B. Taylor.
- 1C3. Controlled Evolution of Highly-Elongated Tokamak Plasmas. S. C. Jardin, F. Hofmann, and F. B. Marcus.
- 1C4. High-Beta Tokamak Stability of Toroidal Plasmas With Elliptical and D-Shaped Cross-Sections. J. Rem, J. P. Goedbloed, G. M. D. Hogeweij, and R. Kleiberger.
- 1C5. Stability of $m = 1$ Configuration To Reflection Symmetry Breaking Modes. W. Park and D. A. Monticello.
- 1C6. Beam Ion Excitation of Ballooning Modes in Tokamaks. J. W. Van Dam and M. N. Rosenbluth.
- 1C7. $m = 1$ Convection Cells In Tokamak Plasmas. R. Denton, J. F. Drake, and R. G. Kleva.

1R POSTER SESSION 2:00 - 3:30 PM Wisconsin Center - Alumni Lounge and Robert P. Lee Lounge

- 1R1. High Beta Tandem Mirror Stability. R. P. Freis, D. Dobrott, and S. Kendrick.
- 1R2. Stability of Anisotropic Pressure Tokamak Equilibria to Ideal MHD Ballooning Modes. C. M. Bishop and R. J. Hastie.
- 1R3. Tokamak Equilibria with Poloidal Pressure Variation and Mass Flow. P. J. Morrison, R. D. Hazeltine, and J. A. Tataronis.
- 1R4. MHD Stability of Plasmas with Aligned Mass Flow. M. Mond and J. A. Tataronis.
- 1R5. Iron Core Field Perturbations and Mirnov Oscillations on LT-4 Tokamak. R. L. Dewar, R. D. Parker, and H. J. Gardner.
- ✓1R6. Resistive MHD Stability of Low Aspect Ratio Tokamaks. T. C. Hender, J. A. Holmes, B. A. Carreras, and L. A. Charlton.
- 1R7. Nonlinear MHD Calculations In Toroidal Geometry. L. A. Charlton, B. A. Carreras, H. R. Hicks, J. A. Holmes, and V. E. Lynch.
- 1R8. Parametric Decay Process of Inhomogeneous Plasmas in the Ion Cyclotron Range of Frequencies. S. C. Chiu.
- 1R9. Study of the Effect of Localized ECH On Transport and Stability In Plasmas. A. H. Kritz, H. Hsuan, A. Cavallo, D. McCune, D. R. Mikkelsen, P. H. Rutherford, and R. B. White.
- 1R10. Analytic Mirror Equilibria With New Long-Thin Terms. D. L. Goodman and J. P. Freidberg.
- 1R11. Low- n Tokamak Ripple Transport, and Its Effect on Rotational Damping. H. E. Mynick.
- 1R12. Numerical Comparison of Strong Langmuir Turbulence Models. M. M. Shen and D. R. Nicholson.
- 1R13. A One-Dimensional Theory For Lower Hybrid Current Drive. R. A. Cairns, V. Fuchs, M. M. Shoucri, K. Hizanidis, and A. Bers.
- 1R14. Effect of Shear and Torus Curvature on $m=2$ Modes In $l=2$ Stellarator Configurations. F. Herrnegger and J. L. Johnson.
- 1R15. Injection of Large Pellets in TFTR: Theory Issues. W. A. Houlberg and H. C. Howe.
- 1R16. Elimination of the Stabilizing Effect of Finite Larmor Radius on Ballooning Modes in Tokamaks and Tandem Mirrors. M. Kotschenreuther and H. L. Berk.
- 1R17. Parallel Viscosity In A Tandem Mirror. K. D. Siebert and J. D. Callen.
- 1R18. Heat Transport By Electrostatic Microturbulence In the Edge Regions of the Caltech Research Tokamak. P. C. Liewer, S. J. Zweben, and R. W. Gould.
- 1R19. Eigenmode Structure and ICRF Heating and Stabilization of Axially Symmetric Systems. C. Litwin, N. Hershkowitz, and J. D. Callen.
- 1R20. Finite Ion-gyroradius Corrections to the Toroidal Tearing Mode. C. T. Hsu, R. D. Hazeltine, and P. J. Morrison.
- 1R21. Local Power Conservation For Linear Wave Propagation In An Inhomogeneous Plasma. R. Sund, J. Scharer, and B. McVey.

- 1R22. Neoclassical Tearing Instabilities In Tokamaks. W. X. Qu and J. D. Callen.
- ✓1R23. MHD Modelling with the Hall Term. F. Kazeminejad, J. N. Leboeuf, F. Brunel, and J. M. Dawson.
- 1R24. Nonlinear Radial Propagation of Drift Wave Turbulence. M. Prakash and C. K. Chu.
- 1R25. Analytical Study of Energetic Ions Slowing Down In Plasmas. F. Najmabadi.
- 1R26. Stellarator Expansion Studies of Heliotron-E. J. L. Johnson, G. Rewoldt, and G. Kuo-Petravic.
- 1R27. Investigations of Long-Thin Mirror Equilibria With the Full 3-D Method As Computed By VEPEC. D. V. Anderson and B. Lane.
- 1R28. Heat Pulse Propagation On TFTR. E. Fredrickson, J. Bell, J. D. Callen, K. Hill, R. Izzo, K. McGuire, D. R. Mikkelsen, N. Sauthoff, and N. Zarnstorff.

1S POSTER SESSION 4:00 - 5:30 PM Wisconsin Center - Alumni Lounge and Robert P. Lee Lounge

- 1S1. Effects of Turbulent Density Fluctuations on Neutral Transport. A. K. Prinja and P. C. Liewer.
- 1S2. Runaway Of Runaway Discharges Through Avalanching. R. Jayakumar and H. H. Fleischmann.
- 1S3. Lagrangian Variational-Principle Derivation Of a General Theorem For Beat-Resonant Mode Coupling, With Appl. To A Nonneutral Plasma. C. Oberman, J. D. Crawford, and A. N. Kaufman.
- 1S4. Lower Hybrid Wave Scattering By Random Density Fluctuations In Inhomogeneous plasmas. W. Grossmann and R. Spigler.
- 1S5. Relaxation of Finite Beta Toroidal Plasmas. Y. C. Kwok, G. Bhattacharjee, and A. H. Glasser.
- 1S6. Derivation of Scaling Laws for Trapping Rates of Passing Ions In a Mirror Cell. R. S. Devoto, L. L. LoDestro, and A. A. Mirin.
- 1S7. Electron Distribution Functions Produced by High Power ECRH. M. R. O'Brien, D. F. H. Start, and A. Boileau.
- ✓1S8. Anomalous Time Behavior of Entropy In a Non-Maxwellian Plasma. I. Jechart.
- 1S9. Modulation of Small Scale Turbulence By Sawtooth Relaxations In the TEXTOR Tokamak - Observation and Interpretation. A. Boileau, H. W. H. Van Andel, M. Von Hellerman, G. Hasselberg, and A. Rogister.
- 1S10. Viscosity Tensor and Toroidal Momentum Confinement of Strongly Rotating Tokamak Plasma. D. J. Sigmar and W. M. Stacey.
- 1S11. Parameter Studies of Fluid Model Wall Plasma Flows. G. Sowers, L. Montierth, and R. L. Morse.
- 1S12. Tandem Mirror Electron Confinement From Weak To Strong ECRH. T. D. Rognlien, Y. Matsuda, and J. J. Stewart, Jr..
- 1S13. Electron Rate Equations and Potentials In ECRH-Driven Tandem-Mirror End Cells. R. H. Cohen.
- 1S14. Simulation of Loss of Plugging In TMX-U Using the TREQ Code. J. M. Gilmore and M. E. Rensink.
- 1S15. Calculation of Sloshing-Ion Buildup In the TMX-U End Cell. R. A. Jong and Y. Matsuda.
- 1S16. Comparison of Proposed Ignition Experiments and Plasma Theory Issues. B. Coppi.
- ✓1S17. Are Tokamak Disruptions Caused By MHD Clump Instability?. D. Tetreault.
- 1S18. Monte Carlo Simulations of Particle Transport In Stellarators. C. D. Beidler, W. N. G. Hitchon, H. E. Mynick, and J. L. Shohet.
- 1S19. RF Stabilization of Interchange Modes In Mirror Plasmas By Resonant Sideband Coupling. J. B. McBride, V. Stefan, and N. A. Krall.
- 1S20. Feedback Control of Magnetic Islands In Tokamaks. R. B. White, P. H. Rutherford, W. Park, and H. P. Furth.
- ✓1S21. Theory of Energetic Trapped Particle-Induced Resistive Ballooning Modes. H. Biglari and L. Chen.
- ✓1S22. Numerical Simulations of "Turbulent Trapping" and the Bump-On-Tail Instability. K. Theilhaber, D. Pesme, and G. Laval.
- 1S23. Equilibrium and Stability of Highly Elongated Tokamaks. R. W. Moore, M. S. Chu, F. J. Helton, F. W. McClain, and H. St John.
- 1S24. Spectrum of Ion-Temperature Gradient Driven Turbulence and Particle Transport In Tokamaks. G. S. Lee and P. H. Diamond.
- ✓1S25. Particle Simulation of the Ion Mixing Mode in a Sheared Magnetic Field. R. D. Sydora, J. N. Leboeuf, G. S. Lee, and P. H. Diamond.
- 1S26. Linear Modes and Nonlinear Vortex States In Inhomogeneous Rotating Plasmas. W. Horton, J. Liu, J. D. Meiss, and N. Zabusky.

- 1S27. Betatron Modified Ion-Acoustic Instability of the Bennett Equilibrium. U. Krishnamurthi, A. Sen, A. S. Sharma, and A. K. Sundaram.

TUESDAY, APRIL 16, 1985

2A REVIEW SESSION 8:30 - 9:30 AM Memorial Union Theater (Chair: D. A. Monticello)

- 2A1. Survey of H-Mode Experiments and Comparison with Theory. F. Wagner.

2B MHD AND TRANSPORT 9:40 - 12:10 AM Wisconsin Center - Lakeshore Room (Chair: P. N. Guzdar)

- 2B1. Ideal MHD Beta-Limits and Scaling Laws. J. Manickam.
2B2. Explosive Coalescence of Magnetic Islands. T. Tajima and J.-I. Sakai.
2B3. Subcritical MHD Turbulence. R. E. Waltz.
2B4. Energy Confinement Time Due To Ballooning Modes In the Large Power Limit. J. P. Freidberg, S. P. Hakkarainen, and D. J. Sigmar.
2B5. Neoclassical MHD Instabilities and Transport In Tokamaks. J. D. Callen and K. C. Shaing.

2P POSTER SESSION 9:40 - 10:55 AM Wisconsin Center - Alumni Lounge and Robert P. Lee Lounge

- 2P1. Nonlinear Wave-Particle Interactions At Cyclotron Harmonics With Collisional Decorrelation. M. D. Carter, D. B. Batchelor, and J. D. Callen.
2P2. A New Short Wavelength Mode. Y. C. Lee, J. Q. Dong, P. N. Guzdar, and C. S. Liu.
2P3. Effect of Electron Tail On Ion Bernstein Modes. J. L. Milovich, B. D. Fried, and G. J. Morales.
2P4. Simulation of High-Beta Tokamak Start-Up. X. L. Li, G. A. Navratil, and C. K. Chu.
2P5. Influence of Openings on Nuclear Characteristics of a Fusion Reactor Blanket. J. S. Brzosko, B. V. Robouch, and L. Ingrosso.
2P6. Vacuum Ripple Fields For Improved MHD Stability. L. L. LoDestro.
2P7. Resonance Absorption vs RF Stabilization. J. A. Byers.
2P8. A Model of the Plasma-Sheath Region Including Secondary Electron Emission and Ion Reflection. L. A. Schwager and C. K. Birdsall.
2P9. Reversed Field Pinch Calculations Using A Reduced Set of Equations. J. A. Holmes and B. A. Carreras.
2P10. Fast Wave Heating In Tokamak and Stellarator Magnetic Fields. E. F. Jaeger, D. B. Batchelor, and H. Weitzner.
2P11. Lower Hybrid Current Ramping In the Presence Of Runaway Electrons and Nonlinear Wave Instabilities. V. S. Chan, C. S. Liu, and Y. C. Lee.
2P12. Helically Symmetric Resistive Equilibria For RFP. Y. Z. Agim and J. A. Tataronis.
2P13. Neoclassical Transport In Tokamaks With Divertors. F. L. Hinton.
2P14. The Establishment of the Electrostatic Field in a Stellarator. J. L. Shohet and W. N. G. Hitchon.
2P15. Correlation Function and Spectral Density Distribution For the Stochastic Motion. L. Bromberg and A. B. Rechester.
2P16. Nearly Perpendicular Wave Propagation At the Fundamental Electron Cyclotron Resonance. K. Imre and H. Weitzner.
2P17. Stability Thresholds for Long Wavelength Precessional Modes in Bumpy Torus Experiments. Y. Z. Zhang and H. L. Berk.
2P18. New Energy Source for Hot Particle Modes. H. V. Wong, H. L. Berk, and K. T. Tsang.
2P19. Numerical Investigation of Trapped Particles and Ballooning Modes in Tokamaks. D. P. Stotler and H. L. Berk.
2P20. Energy Confinement Time of Tokamak Plasma With Auxiliary Heating. T. Ohkawa.
2P21. Ray Tracing of Fast Magnetosonic Waves In Tokamaks Including Mode Conversion Effects. C. K. Phillips, D. Q. Hwang, D. G. Swanson, and L. Ratzan.
2P22. Theory Of the Rippling Instability In Toroidal Devices. A. Register.

- 2P23. Neutral Gas Modeling In STM and TMX-U. B. I. Hauss and T. K. Samec.
2P24. The Cyclotron Maser Instability In Relativistic Plasmas: Wave Growth and Saturation. P. L. Pritchett.
2P25. Equilibrium of Axisymmetric Plasmas With Flow. Y. Baransky and C. K. Chu.

2Q POSTER SESSION 11:00 - 12:15 Wisconsin Center - Alumni Lounge and Robert P. Lee Lounge

- 2Q1. Magnetic Reconnection of a Resistive Doublet In the Adiabatic Limit. M. E. Kress and H. Grad.
2Q2. Large Sawteeth And Minor Disruptions. J. F. Drake and R. G. Kleva.
2Q3. Construction of A Variational Principle For the Steady-State Two-Dimensional Fokker-Planck Equation With Strong RF Diffusion. S. P. Hakkarainen and J. P. Freidberg.
2Q4. Fokker-Planck Calculations of Coulomb Collisional Effects On Kinetic Regime Wall Plasmas. L. Montierth, W. A. Neuman, J. D. McCullen, and R. L. Morse.
2Q5. Sensitivity of the Structure of Kinetic Regime Wall Plasmas To Their (Multitude Of) Physical Parameters. W. A. Neuman, J. D. McCullen, and R. L. Morse.
2Q6. Power Balance Curves and Ignition via Ohmic Heating Alone in an OHTE Device. R. A. Scardovelli and G. H. Miley.
2Q7. Modelling of Current Ramps and Sawtooth Oscillations on TEXT. D. W. Ross, W. H. Miner, and J. C. Wiley.
2Q8. Ion Thermal Transport in the TEXT Tokamak. W. H. Miner, D. W. Ross, A. A. Ware, and J. C. Wiley.
2Q9. Evolution of Twisted Magnetic Fields. E. G. Zweibel and A. H. Boozer.
2Q10. Stabilization of Free Boundary Kinks By External Conductors. M. S. Chance, C. Z. Cheng, J. Manickam, M. Okabayashi, A. Miller, and H. Fishman.
2Q11. Neoclassical Transport Theory in the Banana-Plateau Regime in Nonaxisymmetric Toroidal Plasmas I. K. C. Shaing, S. P. Hirshman, and J. D. Callen.
2Q12. Renormalization Group Theory Techniques In Turbulence. M. Hossain, Y. Zhou, and G. Vahala.
2Q13. Trapped Particles With Favorable and Unfavorable Drift. S. Yoshikawa.
2Q14. Helicity and Helicity Injection. J. M. Finn and T. M. Antonsen, Jr..
2Q15. Flow of Plasma and Magnetic Flux Toward A Wall With Application To Field-Reversed Theta Pinches. L. C. Steinhauer.
2Q16. Study of ICRF Spectroscopy As An Alpha Particle Diagnostic. M. Rosenberg, N. A. Krall, and K. G. Moses.
2Q17. Ballooning Modes In Fluid Dynamics. E. Hameiri.
2Q18. Resistive Ballooning Modes In Helical Axis Stellarators With Longitudinal Mass Flow. M. C. DePassier and W. A. Cooper.
2Q19. Gyrokinetic Particle Simulation of Ion Temperature Gradient Drift Instabilities. W. W. Lee and W. M. Tang.
2Q20. Effects of Localized Modes On Ion Heat Transport. R. Englade, B. Coppi, and S. Migliuolo.
2Q21. A Class of Analytical Solutions For Reversed Pinch Type Configurations. C. Chu and W. Bard.
2Q22. Monte Carlo Calculations In Elmo Bumpy Square. J. S. Tolliver and C. L. Hedrick.
2Q23. Nonlinear Dynamics of Magnetic Islands in High Temperature Tokamak Plasmas. R. Carrera, R. D. Hazeltine, and M. Kotschenreuther.
2Q24. A Numerical Study of Finite Gyroradius Effects on Linear Tearing Modes. J. Q. Dong, Y. C. Lee, and P. N. Guzdar.
2Q25. Trapped-Electron Transport Via Microinstabilities. Y. Hu and F. W. Perkins.

2C RFC/RFP 7:30 - 10:00 PM Wisconsin Center - Lakeshore Room (Chair: D. S. Schnack)

- 2C1. Kinetic Stabilization of the Internal Tilt Instability ($n=1$ Ballooning Mode) in Field-Reversed Configurations. J. L. Schwarzmeier, H. R. Lewis, D. C. Barnes, and C. E. Seyler.
2C2. Sawtooth Oscillations and Gas Puffing in the ZT-40M Reversed-Field Pinch. K. A. Werley, R. A. Nebel, M. M. Pickrell, and G. A. Wurden.
2C3. Driven, Force-Free, Helical, Ohmic, Steady States. L. Turner and S. C. Prager.
2C4. Self-Consistent Dynamo In Reversed Field Pinches. A. Bhattacharjee and E. Hameiri.

2C5. Near Term Tokamak Ignition Experiments. C. E. Wagner.

2R POSTER SESSION 7:30 - 8:45 PM Wisconsin Center - Alumni Lounge and Robert P. Lee Lounge

- 2R1. Interaction Of Fast Waves With Energetic Particles In A High-Density Tokamak. D. K. Bhadra and P. L. Andrews.
- 2R2. Rigorous Bounds On Plasma Transport. R. A. Smith and J. A. Krommes.
- 2R3. ICRF-Driven Radial Diffusion of Energetic Tail Ions In Toroidal Geometry. C. S. Chang.
- 2R4. Bifurcation Theory For Tearing Modes. E. K. Maschke and B. Saramito.
- 2R5. Ohmic Ignition of an Elongated Tokamak. R. W. Harvey, M. S. Chu, P. A. Politzer, and T. Yamagishi.
- 2R6. Simulation of ICRH. I. Gledhill and J. M. Dawson.
- 2R7. Energy Confinement In a High Current Reversed Field Pinch. Z. G. An, G. S. Lee, and P. H. Diamond.
- 2R8. Neoclassical Scaling Law For Tandem Mirror Transport. J. R. Myra, P. J. Catto, and G. L. Francis.
- 2R9. Plasma Flow Through Magnetic Mirrors. E. Zawaideh, F. Najmabadi, and R. W. Conn.
- 2R10. Analytical Theory of Nonlinear $m=1$ Island Growth. R. D. Hazeltine, J. D. Meiss, and P. L. Morrison.
- 2R11. Ballooning Mode Stabilization By Large Gradients In Normal Magnetic Curvature. D. A. Skinner.
- 2R12. Cyclotron Resonance Induced Diffusion. T. Tajima and S. Riyopoulos.
- 2R13. Formation and Heating of a Field-Reversed Configuration In A Coaxial Slow Source. D. C. Barnes and D. D. Schnack.
- 2R14. Nonlinear Multiple-Helicity Calculations of Impurity-Gradient-Driven Turbulence in Tokamaks. L. Garcia, B. A. Carreras, and V. E. Lynch.
- 2R15. Impurity Gradient Driven Turbulence and Particle Confinement In Tokamaks. T. S. Hahm, P. W. Terry, and P. H. Diamond.
- 2R16. Quasilinear Theory of Cyclotron Instability In the Presence of Electron Cyclotron Resonance Heating. R. E. Aamodt and B. Hafizi.
- 2R17. Details of Tokamak Ballooning Stability with Energetic Particles. N. Dominguez, J. W. Van Dam, and M. N. Rosenbluth.
- 2R18. Calculation of the Fully Relativistic Dielectric Tensor In the EC Range. S. Tamor.
- 2R19. Pellet Ablation In A Helical Reversed Field Pinch. J. C. DeVeaux.
- 2R20. Effects On Stability Of Ballooning and Tearing Modes By ECH In the DIII Tokamak. P. L. Andrews and V. S. Chan.
- 2R21. Numerical Resistive MHD Simulation On Long Time Scales. D. S. Harned and D. D. Schnack.
- 2R22. Theory of Fishbone Oscillations. F. Porcelli and B. Coppi.
- 2R23. Numerical Solutions of ICRF Fields In Axisymmetric Mirrors. M. W. Phillips.
- 2R24. The Application of Lie Transform Perturbation Methods To Hamiltonian Field Theories. B. M. Boghosian.
- 2R25. MHD Stabilization of High Beta Mirror Plasma Partially Enclosed By Conducting Wall. X. Z. Li and B. Lane.

2S POSTER SESSION 9:00 - 10:15 PM Wisconsin Center - Alumni Lounge and Robert P. Lee Lounge

- 2S1. Tearing and Ballooning Stable High Beta Tokamaks. M. S. Chu, J. M. Greene, F. J. Helton, J. S. Kim, J. K. Lee, and R. W. Moore.
- 2S2. Nonlinear Interaction of Dissipative Trapped Particle Modes and Drift Waves With RF Fields In the Ion Cyclotron Range of Frequencies. V. Stefan, N. A. Krall, and J. B. McBride.
- 2S3. Flux Regeneration In ZT-40M at High Theta and its Relation to the MHD Model. R. A. Nebel and K. A. Werley.
- 2S4. Nonlinear Evolution of Collisional Drift Instabilities. J. F. Federici, W. W. Lee, and W. M. Tang.
- 2S5. Model Calculations On the Tilt Stabilization of Large-Orbit Rings By Angular Momentum. K. Kupfer and H. H. Fleischmann.
- 2S6. Nonlinear Ion Motion and Stochasticity Induced By ICRF In the Center Cell of a Tandem Mirror. B. Hafizi.
- 2S7. The Nonlinear Behavior of the Line Tied Interchange. S. C. Cowley, R. M. Kulsrud, and D. Ho.

- 2S0. Monte Carlo Modeling of ICRH Experiments In STM and TMX-U. T. K. Samec.
- 2S9. Rate Equations For A Tandem Mirror Plasma. W. M. Nevins, B. M. Boghosian, R. P. Freis, J. M. Gilmore, and M. E. Rensink.
- 2S10. Nonlinear MHD Studies of the CTX Spheromak. A. A. Mirin and A. G. Sgro.
- 2S11. FRC Diffusion Modelling: New Approaches. S. Hamasaki and N. A. Krall.
- 2S12. Resistive Ballooning Modes Driven By Anomalous Transport Effects. A. K. Sundaram.
- 2S13. Determination of the Axial Structure of the Trapped Particle Mode In Tandem Mirrors Via Halo Coupling. A. K. Sen.
- 2S14. Covariant Dynamics of Guiding-Center Plasma, Of Oscillation-Center Plasma, and Of Dissipative Plasma. A. N. Kaufman, P. L. Similon, and B. M. Boghosian.
- 2S15. Self-Consistency Constraints on Turbulent Electromagnetic Relaxation and Transport In Collisionless Plasma. P. W. Terry, T. S. Hahm, and P. H. Diamond.
- 2S16. Current-Convective Heat Losses In Reversed-Field Pinches. J. P. Mondt and J. Weiland.
- 2S17. Statistical Theory of Strong Langmuir Turbulence. G. Z. Sun and D. R. Nicholson.
- 2S18. Energy Cascades In Convective Two-Dimensional Benard Turbulence. C. G. Schultz and R. N. Sudan.
- 2S19. MHD Equilibrium and Stability of Current Carrying Toroidal Plasma. T. Yamagishi, M. S. Chu, J. M. Greene, and J. K. Lee.
- 2S20. Shape Optimization for Small Elongated Tokamaks. F. J. Helton, J. M. Greene, R. W. Moore, and H. St John.
- 2S21. A Mechanism For the Spontaneous Generation Of Toroidal Magnetic Flux In A Conical Theta-Pinch. R. D. Milroy and J. U. Brackbill.
- 2S22. ICRH Wave Propagation Equations In Stellarator Configurations. W. A. Cooper.
- 2S23. Magnetic Well Properties of Modular Stellarators. C. Lilliequist.
- 2S24. Symmetry-Breaking Half-Coalescence Ideal Instability Associated With $m/n=1$ Tearing Islands. J. K. Lee and M. S. Chu.
- 2S25. Inductively Driven Changes In Tokamak Profiles. G. Bateman.

WEDNESDAY, APRIL 17, 1985

3B KINETIC THEORY 9:00 - 12:00 AM Wisconsin Center - Lakeshore Room (Chair: J. W. Van Dam)

- 3B1. New Approach To the Study of Waves In Collisionless and Collisional Plasmas. S. P. Auerbach.
- 3B2. Kinetic Theory and Simulation of Multi-Species Plasmas In Tokamaks Excited With ICRF Microwaves. G. D. Kerbel and M. G. McCoy.
- 3B3. Anisotropy of the Electrostatic Potential In EBT and EBS. C. L. Hedrick.
- 3B4. Effect of Nonlinear Collective Processes On the Confinement of A Pure Electron Plasma. J. D. Crawford, T. M. O'Neill, and J. H. Malmberg.
- 3B5. Electrostatic and Magnetostatic Drift-BGK Modes. P. H. Diamond, T. S. Hahm, and P. W. Terry.
- 3B6. Toroidal MHD Equilibrium Determined by Low-Frequency Wave-Driven Currents. D. A. Ehst and K. Evans, Jr..

3P POSTER SESSION 9:00 - 10:15 AM Wisconsin Center - Alumni Lounge and Robert P. Lee Lounge

- 3P1. Computer Simulation of Driven Alfvén Waves. J. Geary, J. N. Leboeuf, and T. Tajima.
- 3P2. Lorenzian Analysis of the Self-Filamentation Mode. A. B. Hassam.
- 3P3. Global Evaluation of Magnetic Field Lines. A. H. Boozer.
- 3P4. Spheromak Tilt-Shift Stabilization With Particle Rings. C. Mehanian and R. V. Lovelace.
- 3P5. Non-Axisymmetric, Sharp Boundary, Toroidal Equilibria. J. A. Tataronis, H. L. Berk, J. P. Freidberg, and P. J. Morrison.
- 3P6. Investigation of Saturated Tearing Modes In Tokamaks Using The Resistive Chodura-Schluter Method. E. Uchimoto, J. D. Callen, D. A. Skinner, L. Garcia, and B. A. Carreras.
- 3P7. Possible H-Mode Mechanism?. R. J. Goldston.
- 3P8. Stabilization of Resistive Kink Modes for Tokamak Profiles within $q(0) < 1$. A. H. Glasser, H. P. Furth, and H. Selberg.

- 3P9. Comparison of Heavy Impurity Injection and Hydrogen Gas Puff. J. C. Wiley, D. W. Ross, and W. H. Miner.
3P10. Disruptions Driven By External Electric Fields. J. P. Dahlburg, D. Montgomery, W. H. Matthaeus, and G. Doolen.
3P11. Equilibrium and Stability of High-Order-Multipole Tandem Mirrors At Low Beta. T. B. Kaiser, W. A. Newcomb, and L. D. Pearlstein.
3P12. Finite Beta In RFP Relaxation. M. J. Schaffer.
3P13. Alpha-Loss-Cone Alfvén-Wave Instabilities In a Sharp-Boundary Model of a Tandem-Mirror Central Cell. S. K. Ho, G. R. Smith, and W. M. Nevins.
3P14. Alfvén Continuum with Toroidicity. S. Riyopoulos and S. Mahajan.
3P15. FRC Transport Studies Utilizing a Flux Coordinate Representation. E. J. Caramana and K. A. Werley.
3P16. Passing Ion Instabilities In Tandem Thermal Barriers. T. Kammash and G. Zavala.
3P17. Line-tying of Hot Electron Interchange and Trapped Particle Modes. M. J. Gerver and B. Lane.
3P18. Inductively Sustained Toroidal Plasmas with Nested Flux Surfaces. R. W. Moses.
3P19. Anisotropic Pressure Helic Equilibria. R. L. Miller.
3P20. Electron Energy Transport In TFTR. J. Martinell and L. Sugiyama.
3P21. Efficiency of Current Drive In Rotomaks. P. K. Kaw and A. Sen.
3P22. Electron Landau Absorption of A Realistic Spectrum of Lower Hybrid Waves During Current Drive. P. Bonoli and R. Engade.
3P23. Wall Stabilized Tandem Mirror Reactor Study. J. Kesner, G. Shuy, and C. W. Lee.
3P24. The Effect of Runaway Electrons On the Tearing Mode. E. Esarey, K. Molvig, C. O. Beasley, W. I. Van Rij, and T. K. Chu.
3P25. On the Ignition Criterion For Tokamaks. F. W. Perkins and Y. C. Sun.

3Q POSTER SESSION 10:30 - 11:45 AM Wisconsin Center - Alumni Lounge and Robert P. Lee Lounge

- 3Q1. Magnetic Surface Quality. G. Kuo-Petravic and A. H. Boozer.
3Q2. Impurity-Ion Acoustic Instability as the Cause of Sawtooth Disruptions. A. A. Ware.
3Q3. Self-Consistent Beta Calculation In RFP. H. R. Strauss.
3Q4. Magnetic Compression of Ion Rings In the Presence of Background Plasma. P. M. Lyster and R. N. Sudan.
3Q5. Symmetry Breaking in the Noncanonical Hamiltonian Formalism for Fluids and Plasmas. S. Eliezer and P. J. Morrison.
3Q6. Monte Carlo Estimation of Confinement In A Tokamak With Ripple. J. M. Albert and A. H. Boozer.
3Q7. WKB Theory Using Gaussian Wave Packets and Exponential Instability In Wave Systems. R. G. Littlejohn.
3Q8. Hyperbolic Islands Fill Stochastic Phase Space. J. D. Meiss, I. C. Percival, and R. S. MacKay.
3Q9. Particle Simulations of Current Driven Drift Waves. J. N. Leboeuf, R. D. Sydora, D. R. Thayer, and P. H. Diamond.
3Q10. Simulations Of the Effect of ICRF Waves On the Interchange Instability. N. F. Otani.
3Q11. Heating In Igniting Plasmas. L. Sugiyama.
3Q12. Ballooning Instability In a Helic. X. Llobet and H. L. Berk.
3Q13. Configuration Studies For the TJ-II Device. A. Lopez.
3Q14. The Evolution of a Spheromak for Different Resistivity Profiles. A. G. Sgro, G. Marklin, and A. A. Mirin.
3Q15. Nonlinear Stability of Drift-Tearing Modes. B. D. Scott, A. B. Hassam, and J. F. Drake.
3Q16. Asymptotic Theory of Fluids Waves In Relativistic Plasmas. F. Pegoraro and F. Porcelli.
3Q17. Interpretation of Density Profile Anomalies Observed In PDX In Terms of Plasma Flow. R. Gruber, S. Semenzato, F. Troyon, and H. P. Zehrfeld.
3Q18. Studies of a Low Frequency Oscillating Field Current Drive. D. A. Baker, R. F. Gribble, and K. F. Schoenberg.
3Q19. Quadratic Form Approach To Collisionless Internal Kink Modes In Finite-Larmor-Radius Regimes. J. J. Ramos.
3Q20. Universal Drift Wave Stability. D. R. Thayer, R. D. Sydora, J. N. Leboeuf, P. H. Diamond, and T. Tajima.
3Q21. Calculation of the Electron Confinement Time in Stellarators at Reactor Collision Frequencies. O. Betancourt and P. Garabedian.

- 3Q22. Implicit Electromagnetic Particle Simulation Code. E. Montalvo, D. C. Barnes, T. Kamimura, J. N. Leboeuf, and T. Tajima.
- 3Q23. Simulation Study of Electron Bernstein Waves In Bounded Plasma. D. Sultan, V. K. Decyk, and J. M. Dawson.
- 3Q24. Analytic Ballooning Stability Criterion With Finite Shafranov Shift In High Beta Tokamaks. W. H. Choe and J. P. Freidberg.
- 3Q25. Transport Simulations of the Effect of Profile Shape On Alpha Heating In TFTR. M. H. Redi, S. J. Zweben, G. Bateman, and D. R. Mikkelsen.

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LIE ALGEBRAIC METHODS FOR COMPUTING CHARGED
PARTICLE BEAM TRANSPORT

A. DRAGT

PLASMA RESPONSE TO DRIFT-PUMP FIELDS IN TANDEM MIRRORS*

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Drift pumping is a process of removing trapped particles radially by applied fields on the azimuthal drift time scale. Two methods have been considered to generate a suitable perturbed field for TMX-U. One is to induce an azimuthally varying electric potential in the pumping region by modulating the potential-controlling plates at the end of the mirror. Another is to generate an alternating magnetic field by using rf coils in the plug. Plasma response to both perturbations are studied under the paraxial approximation.

Modulating the endplates alters the plasma response by moving loss cone boundary. This effect is incorporated in the linearized drift-kinetic equation as an inhomogeneous boundary condition at the (zero-order) loss cone. The resulting equation can be analyzed as in Reference 1. The perturbed potentials in the center cell and plugs are derived in two limits: $v_{ij} \ll \omega \ll v_{ee}$ and $v_{ee} \ll \omega$.

We study the plasma response to an $m=1$ magnetic drift-pump coil by adding the coil-field to the perturbed field in the MHD energy principle for rigid modes. Variation with respect to the mode amplitude results in an inhomogeneous ballooning equation with a source term proportional to the z -derivative of the drift-pump field. We then solve numerically for the plasma displacement.

The response to an $m=2$ pump coil is obtained by taking advantage of the fact that the pump field has the same symmetry as the main (vacuum) field and a frequency small compared to ω_{MHD} . Self-consistent equilibria are calculated with and without the pump field added to the main field, and the displacement obtained by subtracting the resulting fluxline trajectories.

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Axisymmetric Mirror Plasma Stable to MHD and Alfvén Ion-Cyclotron Modes *

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Recent work has shown that MHD modes in an axisymmetric mirror plasma can be stabilized by effects of FLR and a conducting wall.¹ Pressure anisotropy ($p_{\parallel} < p_{\perp}$) enhances wall stabilization but degrades Alfvén ion-cyclotron (AIC) stability. However, finite axial length effects can restore AIC stability.² We choose a physically reasonable ion distribution function and its associated axial pressure profiles, and we show that rigid-mode ($m=1$) MHD stability and AIC stability can both be achieved with axial scale lengths large enough for conservation of magnetic moments.

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ON THE CONSTRUCTION OF OPTIMAL 3-D MHD EQUILIBRIUM CONFIGURATIONS*

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Although there exists several methods for calculating approximate 3-D MHD equilibrium, many of these are based on variational-moment methods,^{1,2} stellarator expansions³ or averaging techniques,⁴ which typically cannot treat magnetic islands and separatrices. We give a method to construct equilibrium configurations which may optimize the volume of plasma to be contained within a bounding separatrix while simultaneously minimizing the sizes of inner magnetic islands. Our method is based on an analytic calculation which incorporates a power series expansion of the magnetic field and scalar pressure in distance from an arbitrary magnetic axis, coupled with a Hamiltonian formulation of the lines of force.⁵ Two sources of resonances have been identified, one from solving for a single-valued flux function, the second being a manifestation of pressure driven resonances given by the parallel current constraint. Optimal confinement configurations are to be constructed through elimination of these resonances. We give a criterion to eliminate entirely the first source of resonances, and give a method to circumvent the second source of resonances order by order.

*This work supported by NSF under contract No. ECS-8110038.

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Stability of a Hot Electron Symmetric
Tandem Mirror with Thermal Barrier*

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In a simple tandem mirror with symmetric hot electron end cells, the plugging electrostatic potential peaks in the the end cells and leads to differential azimuthal $E \times B$ rotation between the end cells and the center cell. It has been shown¹ that this relative azimuthal rotation between the center cell and the end cells can affect the stability of the hot electron precessional mode significantly. Specifically, when the relative end cell $E \times B$ rotation is opposite to the hot electron precession the stability of the hot electron precessional mode is greatly improved, and the hot electron symmetric tandem mirror can be no more unstable than a quadrupole tandem mirror with the same relative $E \times B$ rotation.

In a hot electron symmetric tandem mirror with thermal barrier, the stability picture is more complicated because a new region due to the thermal barrier has to be considered. It is shown that in general the stability of a hot electron symmetric tandem mirror is the same as the stability of its barrier-plug cell alone, plus an additional limitation on the center cell length such that the center cell Alfvén frequency is higher than the average barrier-plug $E \times B$ drift and the hot electron precession frequency. Stability of the hot electron barrier-plug cell is studied extensively.

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

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Oscillation Center Theory and Ponderomotive Stabilization of Mirrors*

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The use of electromagnetic field in the radio-frequency range offers an attractive alternative for the stabilization of flute modes in axisymmetric mirrors. Oscillation-center theory provides a natural and efficient setting for the study of ponderomotive effects on plasma dynamics and stability. It is extended to include, in a self-consistent way, both low-frequency and high-frequency electromagnetic fields. A single expression, the ponderomotive energy, generates by functional variation not only all the ponderomotive effects (ponderomotive forces and magnetization), but also the wave equation governing the propagation and polarization of the high-frequency field. The self-consistent analysis is essential to ensure energy and momentum conservation, and strongly modifies results of non-self-consistent treatments, especially near the ion gyrofrequency. In the MHD approximation for the low-frequency dynamics, the equations linearized around a stationary equilibrium solution are self-adjoint. A variational principle for the flute growth rate as a functional of the plasma displacement field is derived, and contains three distinct ponderomotive contributions: the first, coming from the equilibrium ponderomotive drifts of the oscillation centers; the second, coming from the ponderomotive magnetization; and the third, coming from the modification of the radiation field due to the plasma displacement (a "quasi-mode coupling" process). Explicit evaluation of the various terms of this principle is made for low- m flute modes, using a plasma slab model. We find in particular that, first, the ion gyroresonance cannot be exploited for an enhanced ponderomotive stabilization; second, the total RF energy necessary to stabilize the flute is a fraction ($\sim \beta$) of the total thermal energy of the plasma; third, small- $k_{\parallel}$ RF fields ($k_{\parallel} < \Omega_i/v_A$) are destabilizing, while large $k_{\parallel}$ are stabilizing, indicating that an optimal antenna may consist of multi-loops properly phased. Other results will be mentioned, such as the effects of minority species and of a thermal distribution on flute stability, the effects of finite generator impedance and its use for RF stabilization (passive feedback), and the limitations imposed by small-wavelength modulation instability caused by the radiation field.

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BALLOONING STABILITY BOUNDARIES WITH PLASMA COMPRESSION*

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ABSTRACT

The resistive compressible ballooning growth-rate-level curves and the ideal compressible ballooning stability boundary are determined in the parameter space of shear-versus-pressure gradient for realistic tokamak equilibria.

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COHERENT CO₂ LASER SCATTERING FOR ALPHA PARTICLE DETECTION

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 Dieter Sigmar , Plasma Fusion Center, M. I. T

ABSTRACT

For Maxwellian alphas, we have shown that in a wide GHz frequency range the alpha particle contribution to the spectral density correlation function can be dominant for fluctuation wavenumbers nearly perpendicular to the external magnetic field. The optimal forward scattering angular range for detection of the scattered power is $(0.8^\circ, 1.2^\circ)$, with significant contributions coming from the alphas with temperature $= 5T_i = 5T_e$ and densities $n/n_e = 0.6\%$.

These results are now generalized to include :

- (1) more realistic alpha particle distribution functions,
- (2) relativistic and finite transit time effects, and
- (3) experimental limitations (angular resolution,...).

The results of using loss-cone alpha particle distribution functions further strengthens the feasibility of using CO₂ laser scattering to determine phase space properties of the alphas.

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Analytic F- θ Curves for Reversed Field Pinches*

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In the absence of internally measured magnetic field distributions in hot, sustained current, reversed field pinch (RFP) experiments, it is common practice to use force-free field models which depart from Taylor's Bessel function lowest energy state in the outer region of the plasma. These models are designed to fit the actual F- θ diagram obtained from external magnetic pickup loop measurements. The models used previously have either discontinuous current densities or require numerical integration to obtain the fields and associated F- θ diagrams.

We have obtained analytic closed form solutions for the cylindrically symmetric, force-free fields $\underline{B}$ where $\nabla \times \underline{B} = \alpha(r)\underline{B}$ for some smooth $\alpha(r)$ vanishing at the wall and closed form parametric solutions of F- θ curves for representing RFPs, thus eliminating discontinuities and the need of numerical integration. These solutions are expressed in terms of easily obtainable Bessel functions of the first kind. The method of solution¹ can easily be generalized to generate an n-parameter family of F- θ curves. Results of fitting the experimental ZT-40 F- θ curves will be given.

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STABILITY OF AN AXISYMMETRIC MIRROR WITH AN ENERGETIC ION COMPONENT

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We examine the stability of a periodic, axisymmetric mirror with an energetic ion component to finite azimuthal mode number interchange and ballooning modes. Using the beam-plasma model¹ with a rigid rotor distribution function, we arrive at a non-self adjoint quadratic form of the dispersion functional. This form involves phase space autocorrelation functions² over energetic orbits that exhibit stochastic as well as periodic behavior. The eigenfunction is represented in terms of a set of global basis functions which are complete. Consequently the quadratic form represents a necessary and sufficient condition for stability. Preliminary numerical results will be presented.

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Trapped Electron Effects on Electrical Conductivity
and Runaway Production*

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Using the bounce-averaged nonlinear Fokker-Planck code CQL, the time evolution of thermal and suprathermal electron velocity distributions due to an applied DC electric field and Coulomb collisions has been simulated. We have obtained values for the neoclassically enhanced resistivity [1], η/η_s , where η_s is the Spitzer resistivity, as a function of inverse aspect ratio ϵ varying from 0 to 1, Z-effective = 1, 2, 3, 5, 10 and $E_{\parallel}/E_D \ll 1$. Here E_D is the Dreicer electric field. For the case Z-effective = 1 analytic estimates exist [2,3] and the code yields agreement with theory.

Through a slight modification of the nonlinear collision operator [4], a heat bath effect is achieved allowing a "dynamic" steady state to be achieved for cases in which $E_{\parallel}$ is large enough to create a significant runaway population. Consequently, we have been able to compute runaway rates for various values of $E_{\parallel}/E_D$ and ϵ , and to compare these in the limit $\epsilon \rightarrow 0$ with earlier work [5].

Finally, the "intermediate" and "slide-away" regimes described in Hui et al. [6] have been realized and examined.

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OPTIMIZATION OF NEUTRAL BEAM INJECTION INTO ATF*

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For the initial phase of operation of the Advanced Toroidal Facility (ATF) at Oak Ridge, heating will be provided by the three ISX-B neutral injection systems. Each of these beams can provide 1.5 MW of 40 keV hydrogen for 300 ms.

Although ATF has very large ports (1 m) for tangential injection, the extremely complex geometry of the vacuum vessel intrudes upon the beam path. Using the present injectors, about 15-20% of the injected beam would hit the wall at locations which are difficult to shield.

The Oak Ridge Stellarator beam deposition code¹, STABIT, has been extensively modified to fully account for the source geometry (grid shape, beam divergence, focal length), injection geometry (source location and aiming), and vacuum vessel geometry. It gives the ion locations in flux coordinates so that it is efficient to integrate the orbits during thermalization.

There are four options that can be used to improve the deposition geometry. The beam line can be moved and aimed. The helical coils interfere with most positions, so very little improvement can be achieved. The focal length of the source can be lengthened. On ISX-B, the focal point was at the small entrance port. On ATF, better performance is achieved by focusing the beam inside of the port, at the place where the helical coil intrudes. The beam divergence of the ISX-B sources is 1.3 degrees. If it is reduced to 1.0 degrees, it yields a dramatically improved performance. Finally, a shield can be placed just outside of the entrance port. The shield can be designed to intercept the trajectories of all particles which would hit the insides of the helical field coils. Although this still leads to a reduction in the power delivered to the plasma, the blocked particles can be handled outside of the vacuum vessel without generating any plasma impurities.

Engineering studies must determine the most cost-effective of these solutions.

* 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.

** Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc.

[1] S. A. Hokin, J. A. Rome, T. C. Hender, R. H. Fowler, "Neutral Beam Heating in Stellarators: a Numerical Approach," ORNL/TM-8530 (March, 1983)

3 D NONLINEAR MHD SIMULATION IN TOROIDAL GEOMETRY

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Development started on a code solving the full compressible and resistive MHD equations. The code is intended to describe the macroscopic dynamic behaviour of realistic (toroidal) plasma configurations, particularly near the β -limit.

Modified cylindrical coordinates x, z, ϕ are used, these being much simpler than Hamada-like coordinates adapted to an initial equilibrium. All quantities are expanded in a Fourier series with respect to the toroidal angle ϕ . A predictor-corrector method is used for the time discretization. As Harned and Kerner's semi-implicit method /1/ is implemented the limitation on the time step is governed by the Shear Alfvén wave and not by the fast compression wave. The corresponding implicit velocity equation in the corrector step is very efficiently solved by fast Fourier transform. In addition, two scalar elliptic equations have to be solved in each time step, this also being done by FFT.

The performance of the code is discussed and first results for toroidal cases are presented.

/1/ D.S. Harned and W. Kerner
J. Comput. Phys., to be published

⁺) Work supported by U.S. Department of Energy
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WAVE-INDUCED CURRENT AND HEATING IN A
NON-HOMOGENEOUS PLASMA*

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ABSTRACT

We examine the effects of plasma non-homogeneity on the current drive calculation by considering wave propagation in a diffuse slab and a diffuse pinch. The linear wave propagation problem is analyzed and the quasi-linear driving terms for current generation are explicitly derived by using the collisional Vlasov equation. Expression for wave-induced heating is also given. Various parameter ranges are discussed.

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HIGHLY-ELONGATED IDEAL FREE-BOUNDARY MAGNETOHYDROSTATIC EQUILIBRIA

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The possibility of achieving Ohmic ignition in highly elongated ($b/a > 6$) tokamak equilibria¹ necessitates the investigation of the formation of such equilibria from an ideal magnetohydrostatic point of view. The GA Technologies group has successfully constructed racetrack and "dogbone" type equilibria with elongation as high as 11 : 1. These equilibria can be achieved starting from widely varying initial current profiles. The final configuration must however have a very flat current profile in order to achieve elongations greater than ~ 6.5 . Internal doublets and triplets have been observed for elongation greater than ~ 7 . Our success in this area is due to a free boundary current scrapeoff algorithm which allows formation of highly elongated equilibria through an arbitrary succession of limited and diverted intermediate states. Both diverted and limited final configurations have been produced.

We discuss the so called "zipper" formation of elongated equilibria and present ideal results. Related papers^{2,3} discuss stability and beta limits of these equilibria.

*Supported by U.S. Department of Energy Contract No. DE-AT03-84ER53158.

¹R.W. Harvey *et al.*, *Ohmic Ignition of an Elongated Tokamak*, this conference.

²R.W. Moore *et al.*, *Equilibrium and Stability of Highly Elongated Tokamaks*, this conference.

³F.J. Helton *et al.*, *Shape Optimization for Small Elongated Tokamaks*, this conference.

SINGULAR FINITE ELEMENT METHODS FOR FINITE BETA PLASMAS

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The singular finite element method forms the basis of the PEST3 code¹ for calculating outer solutions in toroidal resistive stability calculations. Convergence problems have reduced the applicability of the code for finite beta plasmas, where the singular Frobenius solutions are fractional powers of the distance from a rational surface. Analysis of a simple model² shows fundamental limitations in the original approach. A new method is presented, based on a form of Green's function for postprocessing the Galerkin solution, which greatly improves the accuracy and convergence of the generalized Δ' calculation.

1. J. Manickam, R.C. Grimm and R.L. Dewar, Resistive MHD Stability in Tokamaks, in: Energy Modeling and Simulation, Eds. A.S. Kydes et al., Vol. IV of IMACS Transactions on Scientific Computation (North Holland, Amsterdam, 1983) pp. 355 - 360.
2. R.L. Dewar and R.C. Grimm, Singular Finite Element Methods in Plasma Stability Computations - A Simple Model, in: Computational Techniques and Applications: CTAC-83, J. Noye and C. Fletcher, eds. (North Holland, Amsterdam, 1984) pp. 730 - 740.

**ENERGETIC ELECTRON EFFECT
ON MHD MODES IN TOKAMAKS***

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The stable access to the second stability regime of ballooning modes¹ and the destabilization of internal kinks² by the energetic particles have been studied recently. Ion ring devices and hot electron ring in EBT have been proposed for better MHD stabilization. In this paper, we consider the effect of a hot electron component, possibly resulted from electron cyclotron resonance heating, on MHD instabilities in tokamaks. Among them, the external kink was considered to be an obstacle to achieve low- q (limiter $q < 2$) discharge. Possibility of overcoming this barrier by the additional stabilization from hot electrons is considered. The formulation will also be applied to find the stabilization conditions for the internal kinks and the ballooning modes.

*Supported by U.S. Department of Energy Contract No. DE-AT03-84ER53158.

¹M.N. Rosenbluth, S.T. Tsai, J.W. Van Dam, and M.G. Engquist, Phys. Rev. Lett. **51**, 1967 (1983).

²Liu Chen, R.W. White, and M.N. Rosenbluth, Phys. Rev. Lett. **52**, 1122 (1984).

STRONG DAMPING OF ELECTRON CYCLOTRON WAVES
IN NEARLY PARALLEL STRATIFIED PLASMAS*

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ABSTRACT

In mirror-like devices, where the magnetic gradient is along the direction of the magnetic field (parallel stratification), the right circularly polarized component of the E field is not suppressed. The warm plasma dispersion relation predicts essentially total absorption of the extraordinary mode. However, because of the strong damping and the rapid variation of k near resonance, geometric optics is not necessarily valid. Adapting a calculation done by Weitzner¹ for ICRH, we introduce three small parameters, $\epsilon_1 = v_{th}/c$, $\epsilon_2 = c/\omega L$, $\epsilon_3 = (\omega_{pe}/\omega)^2$, and perform a boundary layer analysis in the resonance region. For many parameter values, we prove the extraordinary mode is completely absorbed. The integrodifferential equations are solved numerically.

¹H. Weitzner, Phys. of Fluids 26, 998 (1983).

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ARTIFICIAL INTELLIGENCE METHODS FOR
FACILITATING LARGE-SCALE SCIENTIFIC COMPUTATIONS*

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The magnetic fusion energy research program has been a focal point for the development of large-scale computational modeling of physical systems. This modeling has covered a wide range of methods and applications--from particle-in-cell simulations of basic plasma phenomena, to numerical solutions of partial differential equations describing plasma equilibrium, stability, and transport, to the use of systems analysis methods which anticipate reactor behavior. Despite this diversity, there exist generic features common to many of these models. Foremost among these is the practice of utilizing large-scale numerical computations in a manner which emphasizes understanding the scaling and parametric tendencies of the underlying mathematical model rather than as a means of obtaining specific numerical results. We discuss the use of artificial intelligence-based methodologies to facilitate the analytical process of using such computational models. Specifically, we describe ANALYZ, an expert system which serves as a planning aide for conducting parametric studies with a target prototypical plasma stability code. ANALYZ is implemented in LISP and makes extensive use of symbol and object manipulation, as opposed to numerical manipulation, and utilizes heuristic or "rule of thumb" reasoning processes, as opposed to algorithmically precise reasoning. It interacts either actively or passively with its target FORTRAN code, builds an evolving data base of the code's experiences, and converts the data base into a knowledge base by forming "opinions" about the parametric variations of code results. On being informed of a user's intentions to make a "run" with the target code, ANALYZ attempts to mimic the human reasoning processes which are involved in ascertaining the relevance of prior knowledge of target code behavior to the task at hand and suggests alternative, potentially more efficient ways of acquiring the desired information. While still in a primitive state, ANALYZ serves as an example of the potential applications of the rapidly developing field of artificial intelligence, even to such hard sciences as plasma physics.

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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

**Solution of the Electron's Fokker-Planck Equation
for Tandem Mirror Trapped Particle Modes****H.L. Berk*Institute for Fusion Studies
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In the analysis of trapped particle modes in tandem mirrors, an essential part is played by the collisions of electrons, which cause them to be collisionally transferred between the cells of the tandem during an oscillation period. A general and novel method of solving the wave-kinetic Fokker-Planck equation has been developed. Over most parameter regimes, the solution can be expressed in terms of the original Pastukhov problem, which solves for the steady state particle and energy lifetime of electrons in an electrostatic trap. The limits of the solution is set at high collisionality by the condition that the electrons be long mean free path and at low collisionality by the condition that $\nu > \omega T/|e\Phi|$ ($\nu \equiv$ electron collision time, $\omega \equiv$ wave frequency, $T \equiv$ electron temperature, $|e\Phi| \equiv$ electrostatic field energy). The solution corrects a previous derivation¹ that neglected heat conduction between the plug and central cell. The solution is applied to trapped particle modes in tandem mirrors with equilibrium radial electric fields. A discussion of the modes and their growth and damping rates will be presented.

¹ H.L. Berk, M.N. Rosenbluth, R. Cohen, W. Nevins, IFS Report 160.

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

PONDEROMOTIVE FORCE PUMPING OF TANDEM MIRROR THERMAL BARRIERS

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A method for pumping tandem mirror thermal barriers using an azimuthal ponderomotive force to cause a radial drift of ions will be presented. The idea applies to axisymmetric, as well as quadrupole, configurations and does not require any geodesic curvature of the magnetic field. A properly phased antenna array would be used to create a rotating electric field with an azimuthal gradient in E_+^2 . Ponderomotive force theory and experimental results indicate that a resultant, time dependent force $F \sim \text{grad } E_+^2$ would result. The consequent $F \times B$ drift of ions in the radial direction would pump the thermal barrier.

Calculations for required drift velocities and electric fields will be presented for both the MINIMARS and Phaedrus-Upgrade regimes. A preliminary analysis indicates that the electric fields required for both machines appear reasonable. Thus, this pumping scheme would provide a solution for pumping the thermal barrier in MINIMARS without having to create all of the geodesic curvature for "drift pumping" by the antenna system. Also, it appears likely that Phaedrus-Upgrade could provide an experimental test of the concept within the year.

Three major areas of uncertainty remain: (1) General ponderomotive force theory is still in its early stages; (2) An optimized antenna design is required; and (3) Self-consistent electrostatic potential effects may be important. This paper will address the last two areas.

In summary, RF ponderomotive pumping is conceptually simple, and does not rely on a complicated physics analysis. The basic results to be presented in this paper depend only on the existence of an azimuthal force, whether ponderomotive or of another nature. Some effects, relevant when specializing to ponderomotive force theory, will also be discussed.

This research was supported by Department of Energy contracts DE-AC02-80ER53104 and DE-AS02-78ET52048.

Kinetic Theory of ICRF Stabilization
of Interchange-Ballooning Modes*

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A fully electromagnetic kinetic theory of the effect of ICRF on low frequency curvature driven modes in mirror geometry is presented. The theory includes the direct ponderomotive force effects and sideband mode coupling on an equal footing, and allows for general perpendicular polarizations of the RF wave. We calculate the nonlinear forces on a fluid element by invoking the paraxial expansion and a small Larmor radius ordering. An explicit expression is obtained for the perturbed nonlinear force, and hence the generalized ballooning equation, which is valid for arbitrary (interchange-ballooning) azimuthal mode number m and arbitrary plasma beta. In the high- m interchange limit, a simple dispersion relation results which illustrates the respective roles of the direct ponderomotive force, non-resonant sideband coupling and parametric interaction. Simple limits exist in which each of the effects can be dominant. Depending on the parameter regime, it is possible for the RF to stabilize or destabilize the low frequency wave.

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LOWER-HYBRID CURRENT DRIVE IN THE PRESENCE
OF AN OHMIC ELECTRIC FIELD *

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Two-dimensional Fokker-Planck studies are presented of the combined effect of lower-hybrid (RF) quasilinear diffusion (D_{QL}) and of an ohmic field (E) on the plasma current. The standard linearized collision operator appropriate for runaway tails is employed, so that electron momentum conservation is violated but we compensate for this by adjusting the bulk current and distribution on the basis of the moment equations. In the absence of RF the collisional model thus yields the appropriate runaway rates and we can also recover the correct total current. With RF, strong modifications of both the plasma current and runaway rates can occur depending on the location of the RF spectrum. The principal effect is an E -dependent RF conductivity, valid when the lower bound of the spectrum lies well below the critical velocity. Our calculations of both the RF driven current and runaway rates span the region of E/E_c from 0.005 to 0.04, and of $D_{QL}/v_e^2 v_0$ from 3 to 45, relevant to present-day current-drive experiments.

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Fokker-Planck Calculations for JET ICRF Heating Scenarios,* J. SCHARER, J. JACQUINOT, AND P. LALLIA, University of Wisconsin, Madison, Wisconsin and JET Joint Undertaking, Abingdon, England -- Local time-dependent, anisotropic quasilinear ICRF calculations have been made for JET parameters utilizing a Fokker-Planck code [1]. Fundamental deuterium in tritium, second harmonic tritium and deuterium absorption, velocity space control and enhanced fusion Q and ignition cases with alpha particle production are presented for the experimental program at "high grade" power depositions up to 15 MW. The corresponding spatial species resonances and power deposition profiles for various cases are presented. For minority deuterium fundamental heating at absorbed power levels above 12 MW, deuterium tail fusion enhancement of 1.6 to 1.9 times that for an equivalent Maxwellian is formed near the tokamak core with local $Q = 1$ values for sufficiently long energy confinement times and ICRF pulse widths. The results show that second harmonic deuterium is superior to second harmonic tritium heating for fusion Q production for a given amount of input energy at moderate power levels. Results will also be presented corresponding to current D-He₃ experiments being carried out on JET at megawatt levels.

[1] D. Blackfield and J. Scharer, Nuclear Fusion 22, 255 (1982).

*This research was supported in part by DOE contract DE-AC02-80ER53104-Task III.

SIMULATION OF PLASMA RELAXATION*

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An important aspect of the operation of magnetic fusion experiments such as the Reversed Field Pinch (RFP) and the Spheromak is the phenomenon of plasma relaxation: the natural tendency of a dissipative magnetoplasma system to minimize one integral quantity (such as the magnetic energy) while others remain relatively invariant. Recent three-dimensional computations [1] have shown that the time scale for relaxation is determined by the growth and saturation of $m = 1$ resistive instabilities (long compared to the Alfvén time but short compared with resistive diffusion). Plasma compressibility has also been shown to be important. The computation of these processes with standard MHD codes presents difficulties: codes tied to the compressional or shear Alfvén time scales require large amounts of computer time, and transport codes do not contain the dynamical information necessary to describe the important physical processes. In this paper we describe efficient algorithms that are useful in addressing these problems. These methods require only a fraction of the computer time required by standard codes, and yet contain the relevant relaxation physics and dynamo action. Applications to simulation of F-0 current drive in the RFP are presented.

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1. D. D. Schnack, E. J. Caramana, and R. A. Nebel, Phys. Fluids 28 (1985) (to appear).

⁺ SAIC, Austin, Texas.

* Work supported by USDOE, Contract DE-AC03-83ER53150.

DYNAMO MODEL FOR THE REVERSED-FIELD PINCH IN THE SMALL FLOW AND RESISTIVITY LIMIT

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In a recent study [1] of the reversed-field pinch (RFP), Aydemir and Barnes obtained a steady reversed-field state for an incompressible plasma from a nonlinear, time-dependent, resistive MHD code using helical symmetry, i.e., the system of equations depends spatially on radius r and helical angle $u = \varphi + kz$ only. The plasma was driven by a constant axial electric field. Their conclusions suggest that similar results could be obtained by means of a steady-flow, incompressible, resistive MHD model. In this paper, results from such a steady-flow model are reported.

The basic equations for a driven plasma are derived in helical symmetry and their properties discussed. These equations are fully nonlinear. In the limit of small flow, resistivity, and electric field, the problem consists of solving the helical equivalent of the Grad-Shafranov equation for the helical flux. The pressure and the helical magnetic field are determined from equations that are driven by flows and self-consistent electric fields perpendicular to the helical flux surfaces. These flows and fields can be eliminated by averaging over each flux surface. The resulting one and one-half dimensional system is then solved in a manner suggested by Grad and Hogan [2] in their study of the tokamak. In this technique, the flow and electrical potentials are determined a posteriori.

A simple non-trivial, but uninteresting, solution that is u -independent exists and can be obtained explicitly. By linearization of the basic equations, neighboring, bifurcated u -dependent solutions are also found that depend on the electric field to resistivity ratio.

The fully nonlinear one and one-half dimensional system is integrated using relaxation methods, and driven, resistive, steady-flow solutions are obtained for both the simple u -independent and the helically symmetric cases. The implications of the results are discussed.

¹A. Y. Aydemir and D. C. Barnes, Phys. Rev. Lett. 52, 930 (1984).

²H. Grad and J. Hogan, Phys. Rev. Lett. 24, 1337 (1970).

⁺SAIC, Austin, Texas.

*Work supported by US DOE, under contract DE-AC03-83ER53150.

ALPHA PARTICLE DESTABILIZATION OF BALLOONING MODES
IN TOKAMAKS FOR VARIOUS ENERGY DISTRIBUTIONS*

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ABSTRACT

The effect of alpha particles on tokamak ballooning modes has been examined in the deeply trapped limit for a large aspect ratio tokamak equilibrium. Both a Maxwellian and a slowing down distribution for the alphas have been considered. For parameters where the average hot species precessional drift frequency is in the range of the ballooning mode frequency, such modes can be significantly destabilized. This results in a decreased critical background plasma beta for ballooning instability and a loss of access between first and second stability regions. We examine the regimes of tokamak operation where this can occur and compare the effects of the two different alpha energy distributions in general and for TFTR-like plasmas.

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SHERWOOD THEORY CONFERENCE

ABSTRACT

*HALF-COALESCENCE OF THE $m=1$, $n=1$ MAGNETIC ISLAND :
A MORE GENERAL FORMULATION*

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We present an extension of our previous work concerning the half-coalescence instability of an ($m=1$, $n=1$) magnetic island in Tokamaks. The potential energy is given for an arbitrary shape of the separatrix.

NUMERICAL CALCULATION OF NEOCLASSICAL ION THERMAL CONDUCTIVITY AND VISCOSITY*

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A numerical evaluation of neoclassical ion thermal conductivity for a pure plasma has been performed. The method applies to arbitrary collisionality and finite aspect ratio, with no approximation involved other than truncation. It is based on expansion in a set of basis functions consisting of the product of the Burnett functions and modified trigonometric functions, which are orthogonal with respect to the natural inner product in the neoclassical problem. The exact Fokker-Planck operator can be used because its matrix elements are obtained by a newly derived, efficient generating function technique. The same technique is used for the matrix elements of the other operators occurring in the linearized drift kinetic equation. Comparison with existing works ^{1,2,3} will be made.

The same numerical method is also applied to the calculation of thermal conductivity and viscosity for a rotating plasma. For this problem the method is particularly useful as it is difficult in the conventional approach to treat trapped particle effects in the presence of strong poloidal electric field arising from the centrifugal force.

*Supported by U.S. Department of Energy Contract No. DE-AT03-84ER51044.

¹R.D. Hazeltine *et al.*, Phys. Fluids **16**, 1645 (1973).

²C.S. Chang and F.L. Hinton, Phys. Fluids **25**, 1493 (1982).

³C. Bolton and A.A. Ware, Phys. Fluids **26**, 459 (1983).

A NEW THREE-DIMENSIONAL MHD EQUILIBRIUM CODE*

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We have recently begun testing a new three-dimensional equilibrium code which uses a nonvariational method for solving the equilibrium equations, and which makes no assumptions about the existence of flux surfaces. The basic idea is an old one, updating the magnetic field at each step by first calculating the pressure driven currents and then solving Ampere's law with the appropriate boundary conditions. A recent elegant reformulation of the method by Boozer¹ showed how the associated magnetic differential equations may be accurately solved, and how the solution of Ampere's law in three dimensions may be reduced to the solution of a single Poisson equation. Our primary contributions to the algorithm were: (1) A fast three-dimensional Poisson solver that uses arbitrary, numerically specified coordinates; (2) An automated, efficient algorithm for performing Fourier decomposition along field lines.

Our code uses Fourier expansions in two angular coordinates and finite differencing on a radial grid. For 28 modes and 64 radial grid points the code presently takes about 5 seconds per iteration on the Cray 1. This time will be reduced somewhat further by improvements in coding not yet implemented.

We will present preliminary studies of the properties of the code using analytic equilibria. We will also discuss the application of the code to equilibria having magnetic islands and stochastic field lines.

¹A.H. Boozer, Phys. Fluids 27, 2110 (1984).

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

MODIFIED CONVECTIVE CELLS IN PLASMAS

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Nonlinear equations describing the low frequency (much less than the ion-gyrofrequency Ω_i) electromagnetic perturbations propagating almost perpendicularly to the external magnetic field in the homogeneous plasma are derived using the two-field hydrodynamic equations. In the limit $k_{\parallel} \rightarrow 0$, they reduce to the equations for the electrostatic and the magnetostatic convective cells. The presence of the finite parallel wavenumber $k_{\parallel}$ is responsible for a number of new effects.

In the weak turbulence regime, besides the cascading toward both smaller and larger perpendicular wave numbers, $k_{\perp}$, which is well known in the Navier-Stokes turbulence, there arises also a possibility for the cascading toward larger $k_{\perp}$ only. In the strong turbulence regime, the existence of a two dimensional solitary vortex solution is demonstrated.

The possibility of the efficient parametric drive of the modified convective cells by h.f. electrostatic waves, and their importance for the anomalous particle transport is discussed.

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Energy Transduction in Pellet-Injected Plasmas

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Abstract

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An unexpected feature of the evaporation of refueling pellets in tokamaks is discussed. Specifically, it is shown that steady-state spherically symmetric pellet evaporation leads to a process of "energy transduction" that takes energy from stored electron thermal energy and delivers it to evaporation kinetic energy. This is a non-collisional acceleration process and may be usefully employed in various magnetic fusion devices for controlling the partitioning of the machine stored energy. The ion velocities can strongly exceed the background plasma sound velocity (i.e., $v_i \approx 3 c_s$). Further, it is suggested that energy transduction is responsible for the increased energy confinement time observed in pellet-injected Alcator experiments. Measurements from these experiments are used, first to determine the classical flux-limit parameter, f , and second, to estimate evaporative ion energies. Finally, a number of potentially useful magnetic fusion energy loading schemes that make use of energy transduction will be described.

A PRELIMINARY EXAMINATION OF ICRF HEATING THEORY ON ATF

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The Advanced Toroidal Facility (ATF) is a torsatron type stellarator being constructed at Oak Ridge National Laboratory. Auxiliary heating will be used to attain the desired plasma parameters. The heating of tokamak plasmas via the fast magnetosonic mode in the ion cyclotron range of frequencies (ICRF) has provided a variety of wave absorption processes which have yielded either electron or ion heating. In order to optimally exploit the same physical processes for heating an ATF, we have initiated a study of the theory of mode conversion and wave damping near the ion cyclotron frequency for the stellarator geometry. Several models of increasing sophistication will be discussed. We will first consider an idealized WKB model, using only the cold plasma dispersion relation without a parallel electric field or displacement currents. This model will be used to calculate the cut-offs and ion cyclotron and ion-ion hybrid resonance layers. The next step is the development of a system of differential equations to describe mode conversion and damping. The system is truncated to first order in Larmor radii but includes the effects of explicit gradients. The equations are developed so that a conservation rule for the total energy can be extracted and, thus, yield an explicit expression for the wave damping in differential form.

Numerical Solution of the Fokker-Planck Equation For
Ripple Transport In Stellarators

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ABSTRACT

In order to correctly allow for the effects on ripple transport of particles detrapping, and making many bounces as a toroidal banana before retrapping, a numerical method of solution of the appropriate Fokker-Planck equation by integrating in time has been developed. The calculation is performed in two dimensions, a pitch-angle variable, k^2 , and poloidal angle, θ , solving for the distribution function for helically trapped particles and for both 'forward' and 'backward' streaming particles in the non helically-trapped region. The trapping probability can be specified in a variety of ways, but by choosing it to ensure continuity of flux a result very similar to that of Goldston and Towner¹ was obtained. Care has been taken to ensure that the calculation is precisely flux-conserving.

Results agree broadly with analytic theories in the ' $1/v$ ' and ' v ' regimes. In the regime intermediate between the two the code predicts lower diffusion rates than analytic theory, as does Monte Carlo calculation.²

This work was supported by U.S. Department of Energy under Contract No. DE-AC02-84ER53166 and by the National Science Foundation under Grant No. ECS-8206037.

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ICRF Wave Coupling Propagation and, Heating in Large Tokamaks,* H. ROMERO, N.T. LAM, AND J. SCHARER, University of Wisconsin, Madison, Wisconsin -- A method is presented to investigate the problem of ICRF wave propagation in weakly inhomogeneous plasmas. The problems of strong wave absorption and mode conversion are incorporated in the analysis assuming a non-WKB eikonal form for the perturbed electromagnetic field. The method is restricted in its application, however, to the analysis of problems in which the following two parameters are known to be small quantities: $(\rho/L) \ll 1$ and $(k_{\perp}\rho) \ll 1$, where ρ is the local thermal gyroradius, $k_{\perp} \approx \frac{1}{|\vec{E}|} \left| \frac{d\vec{E}}{dx} \right|$, and L represents the scale length of variation of the unperturbed quantities. A second-order differential equation is obtained for the electromagnetic field. We obtain a numerical solution to this equation employing a variable-step, variable order Adams-Moulton integrating routine. Applying appropriate "radiation boundary conditions" in the vicinity of the strong absorption layer, we calculate the fast-wave transmission and reflection coefficients as well as the ion Bernstein mode conversion coefficients. In addition, we consider the problem of fast-wave coupling into the plasma using a waveguide launching structure. The plasma impedance and the reflection coefficient are evaluated using both a plasma slab matrix model and a differential equation for the electromagnetic field applicable in the plasma edge region. A comparison of the results obtained using these two techniques will be presented. We discuss the influence of the launcher aperture dimensions on the plasma reflection coefficient in order to optimize the coupling properties of the launching structure.

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α - PARTICLE BEHAVIOR IN STELLARATOR REACTORS*

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One possible difficulty with a D-T stellarator fusion reactor is that the thermonuclear α - particles can be born or scattered into superbanana orbits associated with the helical wells.¹ The success of such a reactor depends upon whether or not the α - particles can transfer a sufficient fraction of their energy into the background plasma. In this work, the Fokker-Planck equation was used to calculate the fraction of α - particles lost and the energy which they deposit in the plasma while slowing down. Results indicate that the energy loss is tolerable. The steady-state α - particle density was also calculated and shown to be sufficiently small that no serious "ash" accumulation occurs.

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(Sherwood Theory Conference, Madison, Wisconsin, 15-18th April, 1985).

Resistive Ballooning Modes in a High Temperature Plasma

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It has been pointed out previously⁽¹⁾ that the combined effects of radial temperature gradients and parallel electron thermal conductivity can stabilise the resistive tearing mode in a high temperature plasma. The similarities between the theory of the resistive layer of tearing modes and high mode number resistive ballooning modes led to the prediction⁽²⁾ that a similar effect would be exhibited by the ballooning modes. We have re-analysed this problem within the framework of the cold ion model and the full Braginskii equations for the electrons.

In the ballooning representation these equations may be simplified in the resistive region by averaging over the poloidal period. The resulting equations have been solved numerically, supplemented by analytic treatments of various limiting cases. The conclusion is that, although damped modes exist as in the tearing case, there are nevertheless always unstable resistive ballooning modes present.

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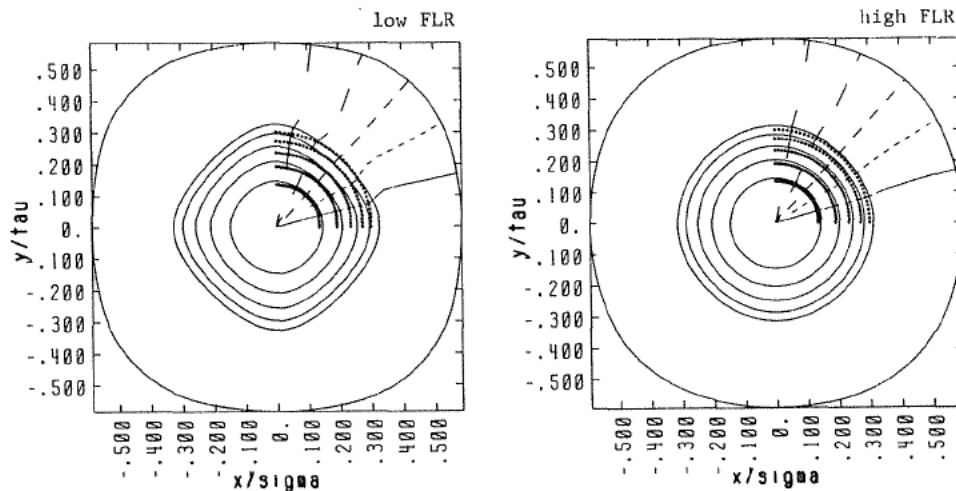
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Three Dimensional Tandem Mirror Equilibria with Finite Larmor Radius Effects.

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A direct iterative method of solving for Tandem equilibria by moving magnetic field lines so as to satisfy the linearized equilibrium equations converges much more rapidly than standard relaxation techniques, typically in under a fifty iterations. At the highest β 's the number of iterations increase, but is still far less than other methods. In quadrupole tandem mirror equilibrium, octupole and higher distortions of the flux surfaces are important which forces us to abandon finite differences in the angle-like flux variable and resort to a spectral decomposition to solve the equilibrium equations. We display equilibria at the high β expected for MFTF-B and show how Finite Larmor Radius (FLR) effects strongly suppress these azimuthal distortions. This is illustrated below for MFTF-B, one of many configurations we have examined.



MFTF-B Flux surfaces in the center cell. At low FLR (left) the plasma surfaces have large octupole distortions. Heavy dots indicate the flux surfaces in the vacuum field. Also shown are θ -lines at equilibrium. With design-point FLR (right) there is little distortion.

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DOUBLE ADIABATIC COMPRESSION OF FIELD-REVERSED CONFIGURATIONS

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The change in the size and shape of field-reversed configurations (FRCs) under wall and flux compression was studied previously using the adiabatic equation of state in MHD, $p/\rho^\gamma = \text{const.}$ ¹ This model not only assumes that there are no losses, but also that the temperature remains isotropic. If the FRC were collisionless, it might be more appropriate to use a double adiabatic model in which there are still no losses, but the temperature need not be isotropic. The problem of FRC compression using this model has been solved for the two limiting cases of FRC equilibria, the low- and high-flux sharp-boundary models. In the high-flux sharp-boundary model, the plasma is magnetized, so the magnetic moment, μ , is taken to be a conserved quantity. The other conserved quantity is the axial action, $v_\parallel \ell$, where ℓ is the length of the FRC. In the low-flux sharp-boundary model, the plasma is unmagnetized, so μ is undefined. However, the radial action takes its place as a conserved quantity. Conservation of the radial action can approximately be expressed by writing $v_\perp r_p = \text{const.}$, where r_p is the outer plasma radius. Because the trapped flux is also conserved, the radial action and the magnetic moment are both proportional to $P_\perp r_p^2/\rho$; the axial action is proportional to $P_\parallel \ell^2/\rho$. By combining these conservation laws with the equilibrium equation and with the equations expressing conservation of trapped flux and particles, the double adiabatic laws for FRC compression can be derived. It can be shown that the average-beta condition now takes the form $(\langle\beta_\perp\rangle + \langle\beta_\parallel\rangle)/2 = 1 - x_s^2/2$. It can also be shown that during wall compression $T_\perp > T_\parallel$, while during flux compression $T_\perp < T_\parallel$.

It is, however, unreasonable to suppose that such a temperature anisotropy will persist. Even without collisions, non-conservation of μ at the ends of the FRC and velocity space instabilities will act to isotropize the temperature. Hence, it is of interest to compare the behavior of an FRC using the fluid adiabatic and double adiabatic models under the assumption that the same kind of compression is applied in both cases, but that at the end the temperature anisotropy arising in the double adiabatic model is relaxed. Thus, both models produce FRCs with isotropic temperatures in the end. For definiteness, this comparison is carried out for the proposed sequence of wall and flux compressions in the proposal for the FRX-D experiment at Los Alamos. Because of the irreversibility of the temperature isotropization, the final state of the double adiabatic model has higher entropy, i.e., higher temperature, and is, consequently, longer.

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INDUCTIVE INHIBITION OF COLD-PLASMA STABILIZATION
OF MIRROR-CONFINED PLASMAS*

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ABSTRACT

Many theoretical attempts to interpret the experimentally-inferred cold-plasma stabilization of flute-like instabilities in mirror-confined plasmas have used rudimentary electrostatic models. These indicated that growth rates could be reduced substantially by a tenuous, finite-length cold plasma terminated by grounded, conducting end walls. However, in many situations of interest, inductive phenomena can inhibit the parallel fluctuating electric fields responsible for the finite-length enhancement of cold-plasma stabilization. In order to investigate these phenomena, we have determined the growth rates of flute-like modes in finite-length cylinders of hot plasma embedded in colder plasmas that extend with arbitrary axial profiles of density along the confining magnetic field lines to end walls. The perturbed fields due to small amplitude flutes are described by $A_{\parallel}$, the parallel component of the vector potential, and ϕ , the scalar potential. Expressions for the perturbed charge and current are obtained from fluid equations as well as kinetic models. Ampere's Law and Poisson's equation are combined to obtain a Schrödinger equation for $\phi(z)$ that has been solved, subject to suitable boundary conditions, for a wide range of plasma parameters. The reduction in growth rate due to finite-length effects is typically less than 50%.

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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

Stability of Islands to Antisymmetric Perturbations in Tokamaks**A. Y. Aydemir*

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Most linear and nonlinear studies of magnetic island dynamics have assumed reflection symmetry for the flux surfaces, $\psi(r, \theta, \zeta) = \psi(r, -\theta, -\zeta)$. Recently, Bussac et al.¹ have proposed that when this artificial symmetry constraint is relaxed, the $m = 1$, $n = 1$ island in tokamaks may become unstable to an antisymmetric ideal MHD mode, thus possibly explaining the fast time scale associated with the disruption phase of the saw-tooth oscillations. Antisymmetric modes may also play a role in major disruptions, since they can alter the time scale for island overlap and the onset of stochasticity. Therefore, whether such symmetry breaking modes exist for $m = 1$ and higher- m islands, and what the consequences of their nonlinear evolution are, need to be investigated. We are studying these questions computationally, using a 3D MHD code that has no symmetry assumptions built into it. In particular, we are examining the possible existence of thresholds in perturbation amplitude and island width.

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Application of Low Frequency Electromagnetic Variational Form to Trapped Particle Modes with Azimuthal Rotation

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We develop the formalism for a variational quadratic form suitable for the analysis of low frequency, $\omega < \Omega_i$ (Ω_i = ion cyclotron frequency), fully electromagnetic perturbations. The analysis employs the long-thin ($B_r < B_z$) and finite Larmor radius ($\rho_i > r_n$) orderings and assumes $Q_L = B_{||} + \xi \cdot \nabla B < \Phi/r^2$ where ξ is the displacement, $\Phi = \xi \cdot \nabla \alpha$ and $B = \nabla \alpha \times \nabla \beta$. The orbit integrals are summed exactly to give the full resonance structure. Using this formalism we consider several applications: (a) It has been shown using MHD equations that at sufficiently high beta, a mirror configuration can be stabilized by the presence of a conducting wall. We extend this analysis by showing that the condition $E_{||} = 0$ gives the lowest energy perturbation and that therefore an electrostatic mode will be stable if the MHD mode is stable. (b) We analyze the radial and axial problem of two coupled cells with differential azimuthal rotation assuming first a low beta sharp pressure profile and then assuming an exponential pressure profile ($n = n_0 \exp(-\alpha/\alpha_0)$, $T = \text{constant}$). (c) We analyze the interaction of MHD and electrostatic ballooning modes in the presence of a strongly stabilizing anchor in the eikonal limit.

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Toroidal Viscosity and Ambipolarity
in the Neoclassical Theory of Axisymmetric Tori*

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To self-consistently evaluate both the toroidal rotation frequency and the radial electric field in a tokamak the two distinct constraints of toroidal momentum conservation and ambipolarity must be invoked. A gyrokinetic derivation of the neoclassical transport equations which permits large toroidal rotations and poloidal precessions is employed to obtain an explicit form for the toroidal viscosity which displays its relation to ambipolarity. To illustrate the general results a plateau regime calculation for a pure plasma is performed. Two important results emerge. First, the poloidal electric field must be obtained from quasi-neutrality to evaluate the collisional contribution to the toroidal viscosity. Second, the rotation and precession speeds can approach the ion thermal speed so that large enhancements of the particle and heat fluxes are possible.

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TRANSPORT CODE SIMULATIONS WITH A COMPREHENSIVE DRIFT-BALLOONING MODEL*

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Transport code simulations have been performed with a comprehensive model for drift-ballooning mode turbulence appropriate to a tokamak. The model covers regimes of low to high collisionality and vanishing to moderate β ($< \frac{1}{2} \beta_{crit}$). Both trapped and circulating electron responses to electric and magnetic perturbations are included. The transport coefficients are based on a simple interpretation of quasilinear theory with saturation at $\tilde{n}/n_0 \approx 1/k_{\perp} L_n$ and fixed mixing length $k_{\perp}^{-1} \approx 3 \rho_s$. Anomalous electron and ion heat transport, plasma transport, and energy exchange are included. The low density scaling $\tau \propto naR^2q$ is recovered for low- β ohmic discharges as a result of the dissipative trapped electron transport. Simulation of the high density saturation of ohmic confinement as well as the high density beam heating regime is currently in progress. Detailed comparisons with DIII data will be presented.

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AXISYMMETRIC STABILITY STUDIES OF A DIVERTOR
LIMITED BEAN-SHAPED TOKAMAK*

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We have investigated the feasibility of controlling the axisymmetric stability and shape variation of a proposed reconfiguration of PBX in which the discharge is limited by divertors at the bean tips. We find that passive conductors located outside the separatrix surface should be sufficient to provide passive stabilization on the fast (ideal) time scale. An orthogonal set of active feedback systems is proposed and shown to be effective in centering the plasma on the mid plane and in maintaining the bean shape for a range of realistic pressure and current distributions. A similar system is shown to be effective in controlling and maintaining a bean shaped plasma inside the TFTR vacuum vessel.

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COMPARISON OF VARIOUS THERMAL CONDUCTION MODELS
ON THE PREDICTION OF DENSITY LIMITS IN TOKAMAK DISCHARGES

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The existence of the density limits (or Murakami limits) has been postulated to exist because of an absence of thermal equilibria beyond a critical density.¹ The thermal conduction model used in the earlier work was derived in the spirit of the Connor, Taylor² prescription by invoking the invariance of a certain set of equations to scaling transformations. In the present work we consider various thermal conduction models. We consider specifically three models: (1) Ohkawa's model; (2) Perkin's trapped particle drift wave turbulence model; and (3) Pogutse and Parail turbulence model. We will present a comparative study of these three models in predicting density limits in ohmically heated tokamaks.

*Work supported by DOE.

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Numerical Simulation of Transport in a Field Reversed Configuration;
Comparison with Experiment*

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The compact torus transport code CTT has been applied to the simulation of the transport time scale evolution of a FRC plasma. The calculation proceeds by alternating between the calculation of a 2-D axi-symmetric equilibrium and 1-D transport. The equilibrium calculation uses flux surface coordinates and finite elements. The transport calculation consist of the simultaneous solution of three 1-D equations for the ion density, electron entropy and ion entropy. The physical processes which are modeled by this calculation are, classical transport, Joule heating of electrons, collisional transfer of energy between ions and electrons, loss of particles due to flow along open field lines, and anomalous transport based on lower-hybrid-drift scaling. Results of the simulation are compared to the FRX-C experiment at Los Alamos National Laboratory. For the high density experiments the experiment and simulation are in good agreement when the electron-ion collision frequency is multiplied by a factor of 4 to 5.

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

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

The rate at which the electrons are ejected, $\frac{dn}{dt}$, is calculated from the electron orbit computation for a given potential well depth. The rate at which passing particles "fill in" the potential well can also be calculated. An estimate of how large the bump in the ambipolar potential grows can be obtained by finding the well depth at which $\frac{dn}{dt}$ approximately equals the "filling" rate. For Phaedrus parameters ($n_0 = 4.0 \times 10^{12} \text{ cm}^{-3}$, $T_e = 20 \text{ eV}$, $\tilde{E}_z \approx 1.0 \text{ V/cm}$) the electron pumping rate balances the "filling" rate at a potential well depth of approximately 40 eV, which is consistent with experimental results.

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THE SPECTRUM OF RESISTIVE VISCOUS MHD*

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ABSTRACT

The spectrum of scalar resistivity and scalar viscosity, incompressible magnetohydrodynamics is calculated in a slab geometry. The approach is similar to Y.-P. Pao's treatment of resistive MHD. The Alfvén continuum of ideal MHD is replaced by point eigenvalues which lie on curves independent of η . The shape of these curves is determined for the previously untreated case of a mode rational surface. Unstable modes occur only when $|\omega| < \eta^{1/3}$ and the tearing and slow interchange modes are analyzed using the WKB expansion. Viscosity removes the accumulation point at $\omega = 0$. Wave propagation in a dissipative medium is discussed.

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EVOLUTION OF A TOKAMAK CLOSE TO THE β LIMIT*

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The evolution of tokamak equilibria close to the theoretical^{1,2} β limit is studied by employing the high β_p reduced equations. Specifically, the q value at the plasma boundary is chosen to be ~ 2 , and the $\epsilon\beta_p$ value is $\gtrsim 0.3$. The current and pressure profiles are assumed to be close to the optimum profile predicted by the ideal ballooning mode theory. We focus on the nonlinear interaction amongst modes with different helicities. The relevance of the simulation to various disruption scenarios will be presented.

*Supported by U.S. Department of Energy Contract No. DE-AT03-84ER53158.

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DIRECT IMPLICIT PARTICLE SIMULATION OF TANDEM MIRROR TRANSPORT*

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This paper introduces the one-dimensional axial simulation code TESS for simulating thermal-barrier formation and loss of plugging in a tandem mirror plasma. We calculate the self-consistent ambipolar potential from data collected from advancing particle ion and electron trajectories. By performing a direct implicit solution for the electric potential [1], we are allowed to use a long time step. An accurate representation of passing and trapped, electron and ion dynamics is rendered by conventional particle simulation and Monte Carlo techniques.

Ion and relativistic electron guiding-center trajectories are calculated. Charge exchange and ionization processes are represented statistically by their averaged rates of occurrence and are allowed to vary axially. The wave heating effects of ECRH and ICRF are modeled in Monte Carlo fashion following Rognlien's scheme [2] based on the formalism of Bernstein and Baxter [3]. Self-consistent binary Coulomb collisions that conserve energy and momentum are similarly modeled [4]. Ions and electrons can be lost axially by transiting out of the end cell. Symmetry is invoked at the center cell midplane. To model radial transport, a probability for radial loss is calculated analytically for classical and neoclassical radial transport with simple (assumed) radial profiles.

The implicit field solution suppresses the electron plasma wave, and the guiding-center equations remove the cyclotron time scales. The fastest time scale is set by axial transit of the particles, which governs the simulation time step. On the slowest time scales, gas is introduced into the center cell which is ionized to replenish plasma losses and heated by ICRF; sloshing ions and pumping of trapped ions result from charge exchange in the end cells; and hot electrons are created locally by ECRH. Startup of a tandem mirror and maintenance of a thermal barrier and end plugging will be simulated.

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HIGH FREQUENCY MODES IN TOROIDAL PLASMAS*

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Electromagnetic modes with frequencies in the ion cyclotron range are examined for a two ion species plasma in a toroidal configuration.¹ These modes are important for studies of plasma depolarization processes^{2,3}, and for radio frequency and neutral beam heating of toroidal plasmas.

We adopt the geometrical optics approximation in order to obtain the relevant rays equations. The equations are solved, both analytically and numerically, looking for radial localized modes.

We found that the existence of the localized modes in a toroidal configuration depends on the assumed density profile. In fact, a resonance between the poloidal and radial motion of the modes may occur for a certain class of particle density profiles. At resonance, the radial motion shows a secular behavior that prevents the possibility of having radial localized modes. The present state of our analysis indicates that the class of profiles for which this secular behavior is found, is relatively narrow.

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ION-VISCOSITY EFFECTS ON $m^0=1$ MODES

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The theory of collisional $m^0=1$ modes based on the two-fluid Braginskii model¹ raised two problems concerning modes in the drift-tearing regime: (i) these modes tend to become nonlocalized at high temperatures; (ii) at the same time, the effect of the finite drift wave frequency is to introduce fine structure (spatial oscillations) in the radial profile of these modes on scale lengths of the order of the ion gyro-radius, breaking the validity of the adopted fluid model. It was then stated¹ that the inclusion of the perpendicular ion viscosity tends to both "smooth out" the fine structure of the mode radial profile and maintain the mode localized even in the higher temperature regimes, as this effect is proportional to higher order derivatives of the mode eigenfunction. This prediction was then confirmed by a subsequent numerical work.² Recently, analytical progress has been made possible by the introduction of a Fourier space representation of resistive modes with low poloidal wavenumbers.³ In the Fourier space, the problem of ion-viscosity effects on $m^0=1$ modes is greatly simplified, as it yields a second-order differential equation with local boundary conditions, instead of a fourth-order differential equation with integral boundary conditions in the coordinate space. An analytic solution to the mode equation in the Fourier space can be obtained by the use of asymptotic matching techniques. While this solution substantially confirms the previous numerical results, it provides quantitative estimates for the ratio of the ion gyroradius over the width of the singular layer as a function of the plasma parameters, and therefore sets new limits for the validity of the adopted fluid model.

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The Computation of Single Helicity RFP
Ohmic States*

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An Ohmic State in an RFP is a time independent solution to the resistive MHD equations having a reversed toroidal field which is sustained by $V \times B$ electric fields in the interior, and driven by an inductive E_z field at the wall.

The magnetic field of a single helicity Ohmic State is computed by simultaneously solving a 2-D helical Grad-Shafranov equation and a 1-D surface averaged parallel Ohms' law. The diffusion velocity and density profile are then determined from the perpendicular Ohms' law and the continuity equation.

The normal components of the velocity and magnetic field vanish at the boundary and energy is supplied by an $E_z \times B_\theta$ Poynting vector sustained by a pressure gradient at the wall.

The inclusion of Hall effect terms is shown not to alter the magnetic field.

The possibility of finding analytic solutions for certain special choices of pitch and pressure profiles is considered.

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A MAGNETIC AND INERTIAL HYBRID FUSION*

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A novel fusion scheme, "a disposable mini-spheromac", is proposed in which a high intensity laser produced magnetic field is used to contain heat while the inertia of a heavy metallic shell is used to contain the plasma pressure as well as the magnetic field.

The thermal shield by the magnetic field reduces the sound speed of the metallic pressure container which elongates the inertial confinement time by a few orders of magnitudes compared with ordinary inertial fusions. This leads to a new regime in fusion plasma parameters with $n \approx 10^{21} \text{ cm}^{-3}$ and $B \sim 10^3 \text{ T}$ with an input energy of a few MJ and an output energy of a few GJ per pulse.

This new scheme is believed to resolve some fundamental difficulties in reactor designs of conventional magnetic as well as inertial fusions.

* The work was performed at the Institute of Laser Engineering, Osaka University, Osaka Japan.

Strong Interaction of Resonant Particles with Wavepackets

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The Hamiltonian, $H = p^2/2m + e\phi(x-v_g t)\cos(kx-\omega t)$, of a particle moving in a wavepacket is analyzed in the narrow spectrum limit. Numerical calculations on this model were carried out by Fuchs *et al*¹, who introduced this Hamiltonian as a model for narrow spectrum turbulence. They measured the velocity diffusion in the narrow spectrum limit and found strong disagreement with resonance broadening theory. (Good agreement with quasilinear theory was found in the opposite limit.) Disagreement with resonance broadening theory has also been found by other numerical studies of different situations²⁻⁴.

The present study uses the analytic techniques developed by Tennyson *et al*⁵ for the problem of separatrix crossing. These techniques must be modified because the usual action is not the lowest order adiabatic invariant. A new adiabatic invariant is found. Use of this adiabatic invariant allows one to predict which particles will be reflected and where the reflection will take place. Diffusion arises at separatrix crossings (trapping and detrapping) during which the adiabatic invariant is no longer conserved. Two distinct processes contribute to the diffusion: (1) spreading due to loss of adiabatic invariance, and (2) bifurcation of the lowest order adiabatic invariant at the crossing location.

The analysis shows that there are two regimes in the narrow spectrum limit. The two regimes depend on the size of $\alpha \equiv |e\phi/m|/|v_\phi - v_g|^2$. For $\alpha \ll 1$, few particles are reflected, and the velocity diffusion is due primarily to bifurcation. In the opposite limit, a significant number of particles are reflected, and the diffusion is due primarily to spreading at the separatrix crossing.

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JET MHD

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The experimental data from JET present a range of theoretical problems. Some of these re-emphasise long-standing difficulties of interpretation of tokamak experiments, others appear to be new. The principal purpose of this paper is to confront theory and experiment under the following headings:

Disruptions

The central problem of practical interest is that of understanding the conditions which lead to a disruption. With regard to density limit disruptions the idea that power balance plays a crucial role is attractive. A careful analysis of the sequence of events has led to a theoretical model which seems to describe the essential elements of the observed behaviour.

Analysis of the current quench phase in JET reveals remarkable plasma conditions with a power input sometimes approaching 1 GW. Interpretation of the results in terms of radiation cooling seems to be successful.

Sawteeth

The evidence on sawtooth oscillations presents severe difficulties for the various theoretical models.

Current Formation

The observations of $m = 2$ instabilities during the current rise when the surface value of $q \simeq 11$ has led to a model which predicts current formation at the axis rather than in a skin.

SHERWOOD CONFERENCE 1985

TOROIDAL MINIMUM-B EQUILIBRIA AND RELATED CONFIGURATIONSC M Bishop & J B Taylor

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Abstract

Minimum-B mirror systems provide stable short-term confinement of anisotropic plasma, but have open field lines; longer term confinement requires scalar-pressure and closed toroidal magnetic surfaces. It is well-known that toroidal minimum- B vacuum magnetic fields do not exist and hence there are no low- β toroidal minimum-B equilibria. Despite this we have constructed, using a novel approach to the Grad-Shafranov equation, a set of finite- β toroidal minimum-B equilibria (ie equilibria in which the toroidal magnetic surfaces coincide with the constant-B contours and in which B increases and P decreases with distance from the magnetic axis). We have also shown that these are the only possible axisymmetric toroidal minimum-B equilibria. In these configurations all guiding-centre drifts lie in the magnetic surface, so there is no neoclassically enhanced transport, and they are free of all trapped particle effects. Unfortunately, however, they do not share the intrinsic stability properties of their mirror counterparts.

Toroidal minimum-B equilibria are in fact members of a wider class of equilibria which, although differing in magnetic field and pressure profile, all correspond to a single and unique geometric configuration.

CONTROLLED EVOLUTION OF HIGHLY-ELONGATED
TOKAMAK PLASMAS*

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It is demonstrated numerically that a tokamak plasma can be evolved continuously from a near-circular cross-section shape to a $4/1$ vertically elongated racetrack. All intermediate stages and the final state are stable to axisymmetric MHD modes. The fast (ideal) time scale stabilization is provided by a finite conductivity vacuum vessel which is always close to 3 sides of the evolving plasma. The resistive time scale stability is provided by an orthogonal set of active feedback systems that maintain positional control in both the vertical and radial directions, and also control the plasma shape and proximity to the vacuum vessel. The feedback sensing signals are continuously interpolated from a set of stationary magnetic pickup coils. The calculations are performed using the free-boundary tokamak simulation code STARTUP. Circuit and flux diffusion equations are solved for the poloidal field coils and passive conductors, while the MHD equations are solved for the plasma evolution.

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HIGH-BETA TOKAMAK STABILITY OF TOROIDAL PLASMAS WITH ELLIPTICAL AND D-SHAPED CROSS-SECTIONS

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A numerical program HBT has been developed by which global and local stability of high-beta plasmas can be studied [1]. A high-beta tokamak equilibrium is characterized by the shape of the cross-section, the value of $\epsilon\beta_p$ (inverse aspect ratio times beta poloidal), and unit profiles for a quantity $\Gamma(\psi)$ and for the pressure gradient $\Pi(\psi)$. At the magnetic axis $\psi = 0$, $\Gamma(0) = \Pi(0) = 1$. The average beta $\langle\beta/\epsilon\rangle$ and $\epsilon\beta_p$ are related through $\epsilon\beta_p = \eta \langle\beta/\epsilon\rangle q^{*2}$, where $\eta \equiv S/\pi a^2 e^2$ ($= 1$ for a circle) and q^* represents the toroidal current "safety factor"; S and e are the area and the elongation of the cross-section ($e = \int dl/2\pi a$). The global stability is represented in a $\epsilon\beta_p$ versus q^* diagram.

Stability studies of equilibria with broad current profiles, where q_1/q_0 takes on values between 1.5 and 2.0 (q_1 = safety factor at the boundary, q_0 = safety factor on the magnetic axis) show that at large currents ($q^* \sim 1-3$) global stability is largely determined by the external kinks and internal modes. At low values of $\epsilon\beta_p$ the external kinks lead to unstable regions just below integer values of q^* (no stabilizing wall). These regions merge with the ones due to the internal modes that lie adjacent to the curves $q_0 = 1$ and 2. This results in stable islands above $q^* = 1, 2$ and 3. The most stable plasmas are found for currents near $q^* = 2$.

For a plasma with a circular cross-section it was possible to attain a stable beta $\langle\beta\rangle/\epsilon = 0.082$ by shaping the current profile so that the gradient near the boundary is sufficiently small (stabilizing the external modes) while keeping q_1/q_0 smaller than 2 in order that the internal $m = 1$ mode does not destroy the stability [2]. This value is in close agreement with Troyon's scaling law [3] which in terms of our parameters consists of a linear relationship between $\langle\beta\rangle/\epsilon$ and e/q^* : $\langle\beta\rangle/\epsilon = 0.16/q^*$ as compared to $\langle\beta\rangle/\epsilon = 0.14/q^*$ found by Troyon. The same current and pressure profiles ($\Gamma(\psi)$ and $\Pi(\psi)$) result in optimum values of beta in elliptical and D-shaped cross-sections. The main effect of the elongation lies in permitting higher currents. The overall stability of the D-shaped cross-section is better than that of the ellipse (same b/a). For $b/a = 1.2$, this results for a D in a coefficient in Troyon's scaling law that is higher than for the circle: $\langle\beta\rangle q^*/\epsilon e = 0.182$.

This work was performed under the Euratom-FOM association agreement with financial support from ZWO and Euratom.

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STABILITY OF $M = 1$ CONFIGURATION
TO REFLECTION SYMMETRY BREAKING MODES*

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Recently, Bussac et al.,¹ have reported that a plasma state with $m = 1$ island is unstable to an ideal mode which breaks the reflection [$f(\theta, \phi) = \pm f(-\theta, -\phi)$] symmetry. This so called half - coalescence instability is reportedly confirmed by several numerical simulation studies. This instability, if it exists, would give a quite different picture of the sawtooth oscillation and also indicate that many of initial value calculations have to be reexamined because they assume reflection symmetry. However, above results are at variance with our previous experience with non-symmetrized codes,²⁻⁴ where we did not encounter any reflection symmetry breaking instability. In the light of the above studies, we reexamined the stability of reflection symmetry breaking mode in configurations with a $m = 1$ island.

Using the reduced tokamak equations (which were used in the aforementioned studies), a configuration with a $m = 1$ island results in a singular equilibrium state. To numerically resolve the singularity, the artificial field technique³ is used. The states we studied were found to be stable both linearly and nonlinearly to the reflection symmetry breaking mode. Using the full MHD equations in a cylindrical geometry, nonsingular equilibrium states with $m = 1$ island can be found. These states are again found to be stable. The reasons for the discrepancy between our results and the aforementioned studies will be also discussed.

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Beam Ion Excitation of Ballooning Modes in Tokamaks**J.W. Van Dam and M.N. Rosenbluth*

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Energetic trapped ions created in a tokamak by neutral beam injection (or cyclotron heating or α particles) are able to destabilize ideal ballooning modes through resonant interaction at their curvature drift frequency. Recently this mechanism was proposed¹ to explain the high-frequency "precursor" to the fishbone oscillations observed in PDX.

Using the large-aspect-ratio model tokamak equilibrium, we have investigated an integro-differential ballooning mode equation with a resonance term that describes deeply trapped particles. In the limit $\omega_{dh}/\omega_A \ll 1$, relevant to the PDX parameters, where ω_{dh} is the hot ion magnetic drift frequency and $\omega_A = v_A/qR$ is the Alfvén frequency, a dispersion relation can be derived by asymptotic matching. The marginal stability boundaries thus obtained for the resonant ($\omega/\omega_{dh} \simeq 1$) and nonresonant ($\omega/\omega_{dh} \simeq 0$) branches show that relatively small hot particle beta values, β_h , can resonantly excite the ballooning mode. Approximately, the condition $\epsilon\beta_{pol,h} > \text{Max}(8\omega_{dh}/\pi^3\omega_A, 2SM_e/\pi)$ is sufficient for instability, where ϵ is the inverse aspect ratio, S is the local shear, and M_e is a measure of the stability of the nonresonant branch. This resonant destabilization is absent for a "sloshing"-type energetic particle population with average reversed drift. In the high-temperature limit $\omega_{dh}/\omega_A \gg 1$, we recover enhanced stabilization due to the presence of hot particles.² However, the stable continuum has gaps at $\omega/\omega_A \gtrsim n/2$ ($n = 1, 2, 3, \dots$), with a discrete eigenmode in each gap. Weak resonant effects shift its frequency. Numerical and analytical results will be presented.

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m = 1 CONVECTION CELLS IN TOKAMAK PLASMAS

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A detailed study of $q = 1$ internal disruption in tokamaks has been carried out by integrating the 2-D resistive MHD equations including the self-consistent evolution of the temperature T . Ohmic heating as well as parallel and perpendicular thermal conduction are retained. For all cases considered over a wide range of parameters and initial conditions the plasma evolves into a quasi-steady state in which a large amplitude $m = 1$ convective cell is formed in the center of the plasma column where the initially peaked current profile has been flattened so that $dq/dr \approx 0$ and $q \approx 1$. Periodic sawteeth,¹ which have been observed over a limited range of parameters, appear only as a transient before decaying away.

The convective cell is driven by the resistivity gradient in a manner similar to the rippling mode.² Unlike the usual rippling mode, however, parallel thermal conduction does not strongly affect the cell since $dq/dr \approx 0$. A simple set of nonlinear equations has been derived which describe this phenomena. The time asymptotic solution of these equations corresponds to a stable fixed point which reproduces the properties of the convective cell.

The possible relation between the convective cell and the continuous $m = 1$ activity observed in many low β tokamak discharges and the implications of our results for understanding sawtooth behavior will be discussed.

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HIGH BETA TANDEM MIRROR STABILITY*

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In current tandem mirror designs, MHD stability is provided by "minimum-B" end-cells [1]. These cells represent a significant fraction of the cost of the tandem mirror device. Both the end-cell material costs and cell power requirement costs are proportional to the cell volume. It is important, therefore, to reduce this end-cell volume.

Recent theoretical work [2,3] has suggested that the central-cell plasma may be stabilized by a combination of finite gyroradius effects and the proximity of a close fitting conducting wall. In order to utilize this means of stabilization, very high beta of the order of 80% to 90% is required. Although this passive means of stabilization would be by far the most economical, it is clear that some method is required to reach this high beta regime. The use of hot electron rings in axisymmetric end-cells is suggested in this study.

Stabilization of an axisymmetric tandem mirror by means of e-rings and conducting walls has been investigated analytically and computationally in the paraxial limit. The major computational tool is the code FLORA [4], which has been modified for this study. It is found that the ring beta β_r required for stability, as a function of central-cell beta β_c , increases for low β_c , has a maximum, and decreases for high β_c . Low beta stability is obtained by the e-ring, while high beta stabilization is achieved by wall proximity. The plasma radius increases with increasing β_c and, for fixed wall radius, the plasma-wall gap decreases, thus tending to stabilize the plasma.

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(Sherwood Theory Conference, Madison, Wisconsin, USA, 15-17 April, 1985)

Stability of Anisotropic Pressure Tokamak
Equilibria to Ideal MHD Ballooning Modes

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The effect of strong pressure anisotropy on ideal mhd ballooning modes has been analysed for a large aspect ratio tokamak. The equilibrium is calculated locally in the neighbourhood of a circular magnetic surface on which the perpendicular pressure $p_{\perp}(\theta)$ and poloidal magnetic field $B_p(\theta)$ are specified functions of the poloidal angle θ .

It is found that outward weighting of the perpendicular pressure, $p_{\perp} = p_{\perp 0}(1 + \eta \cos \theta)$ with $\eta > 0$ and $\theta = 0$ on the outside of the cross-section, is destabilising, especially at low shear. This arises both from the unfavourable weighting of radial pressure gradients towards the outside, and from the destabilising contributions from the longitudinal pressure gradient. An inward shift of the pressure surfaces ($\eta < 0$) is found to be stabilising, in agreement with earlier work. These results continue to hold when the equilibrium outward shift of the flux surfaces is included in the model.

In addition to the effect of poloidal modulation of the perpendicular pressure, it is found that an excess of perpendicular pressure ($p_{\perp 0} > p_{\parallel}$) is destabilising.

We conclude that an important criterion in optimising auxiliary heating schemes should be the avoidance of particle distribution functions which generate outward shifts in the perpendicular pressure ($p_{\perp}(0) > p_{\perp}(\pi)$).

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Tokamak Equilibria with Poloidal Pressure Variation and Mass Flow*

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The lowest order requirement of conventional equilibrium theory, $\mathbf{B} \cdot \nabla P = 0$, where $\mathbf{B}$ is the magnetic field and P is the plasma pressure, is apparently violated in certain tokamak experiments¹, especially where auxilliary heating is employed. Some pressure variation on flux surfaces always arises from FLR corrections to equilibrium force balance, but the observed variations seem sufficiently large to require significant plasma flow. The inherent nonlinearity of the rotating equilibrium problem suggests analysis in terms of reduced fluid models, in which toroidal curvature effects are simplified, and the nonlinearities are expressed in terms of Poisson brackets. Two special cases of the reduced four-field model² are considered here: the first is similar to that of Hulbert and Perkins¹, including the Hall term in Ohm's law but assuming cold ions; the second is a compressible version of reduced MHD (CRMHD²). Generalized equilibrium equations are obtained by variation of an appropriate potential, $I[\psi_1, \psi_2 \dots]$, where the ψ_i represent reduced field variables, and I is a linear combination of the Hamiltonian functional and the Casimir invariants.³ Parallel pressure gradients arise naturally in both models, due to toroidal curvature, plasma vorticity and, in particular, plasma flow along the magnetic field.

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SHERWOOD THEORY MEETING 1985

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MHD Stability of Plasmas with Aligned Mass Flow**M. Mond*

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The linear magnetohydrodynamic stability of plasmas with sub-Alfvénic flows aligned parallel to the equilibrium magnetic field is explored. Subject to the constraints that the plasma is incompressible, inviscid and perfectly conducting, it is demonstrated that stabilizing effects appear as the flow speed approaches the Alfvén speed. The screw pinch plasma is treated explicitly, but it is conjectured that the conclusions of the analysis apply to other equilibrium configurations. The present paper is a generalization of a study by S. Chandrasekhar on the stability properties of ideal MHD plasmas with incompressible, aligned, mass flow. Using an energy principle, Chandrasekhar demonstrated linear stability if the flow speed equals the local Alfvén speed. The geometry assumed by him is arbitrary. In the sub-Alfvénic regime treated in this paper, no energy principle exists. The stability analysis is based on solutions of the eigenvalue problem governing the allowed complex frequencies of linear modes.

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RESISTIVE MHD STABILITY OF LOW ASPECT RATIO TOKAMAKS*

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The linear and nonlinear resistive MHD stability of low aspect ratio tokamaks is studied using the FAR code [1]. Extensive scans of linear stability for $m = 2$ and $m = 3$ modes have been made. For aspect ratio scans in which the q -profile is maintained constant, it is found that decreasing the aspect ratio has a marked stabilizing effect. While for scans in which the current profile is held constant decreasing the aspect ratio has only a modest stabilizing effect. Nonlinear calculations will be presented to show the effects of aspect ratio on nonlinear stability and disruptions. The effects on linear stability of elliptic and triangular shaping have also been studied. It is found that shaping has only a modest effect on stability. Results on the resistive stability of equilibria optimized to give the maximum stable β to external kinks and ballooning modes [2] will also be presented.

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IRON CORE FIELD PERTURBATIONS AND MIRNOV OSCILLATIONS
ON LT-4 TOKAMAK

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The LT-4 Tokamak¹ has a single-sided iron core which produces both $n = 0$ and $n \geq 1$ perturbations on the poloidal fields which would be expected in an air cored tokamak. The $n = 0$ component can be fitted to an axisymmetric core model² and provides an important part of the vertical field for equilibrium. A new model using image magnetic poles and boundary collocation provides a simple method for approximating the full 3D field. By using field line tracing it is estimated that the core produces a static island at the $q = 2$ surface with a width of order 10 % of the minor radius, comparable to typical $n = 1$, $m = 2$ tearing mode widths. The observed³ dependence of the magnetic fluctuations as a function of q_a , the safety factor at the limiter, can be reproduced using the current profile parametrization of Carreras et al.⁴, consistently with the Thompson scattering temperature profile, provided that a mode locking mechanism is invoked to cut off mode rotation when the unperturbed tearing mode width falls below the width of the static island due to the core.

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Nonlinear M.H.D. Calculations in Toroidal Geometry*

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A resistive M.H.D. model derived for the large aspect ratio has been successful in understanding low frequency M.H.D. activity in tokamaks.¹ Experimental results indicate, however, that the internal kink mode could play a role at high injection power.² Since this mode is excluded by the ordering assumptions used for the large aspect ratio method, work was started to construct a computer code using a formalism which does not utilize these ordering assumptions. For this purpose, incompressible equations were developed which are similar to those of Azumi et al.³ Linear calculations from the resulting computer code FAR were presented earlier⁴ where it was found that the $n = 1$ results using the new formalism were identical to those obtained with large aspect ratio ordering at high β ($\beta_0 > 15\%$ where β_0 is the value of β at the magnetic axis) and at low β ($\beta_0 < 1\%$). At intermediate values of β , the FAR approach shows that the most unstable mode is the internal kink which is excluded by the large aspect ratio formalism.

These calculations have now been extended to full nonlinear evolution. Under investigation is the nonlinear evolution above the internal kink threshold and also the low β reconnection behavior responsible for the "sawtoothing" phenomena in tokamaks. For the latter, it has been found in cylindrical calculations that the nonlinear tearing mode responsible for sawtoothing at larger aspect ratio saturates at small aspect ratio. Toroidal studies of this behavior are underway. Results of these studies will be presented.

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PARAMETRIC DECAY PROCESS
OF INHOMOGENEOUS PLASMAS IN
THE ION CYCLOTRON RANGE OF FREQUENCIES*

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RF-heating near the ion cyclotron range of frequencies is of importance in fusion devices. In toroidal devices,¹ there has been evidence of parametric decay processes. In mirrors, possible stabilization of interchange mode by parametric process was demonstrated experimentally² and theoretically.³ Study of parametric decay near ICRF is thus of great interest. In this paper, we study the parametric decay of ICRF in an inhomogeneous plasma in general magnetic geometry. The calculation is restricted to processes where the daughter wave is much less than Ω_i . Using the nonlinear gyrokinetic equations, the nonlinear dispersion relation including triad interactions is derived. This is applied to interaction of ICRF with density fluctuations in tokamaks and parametric stabilization of interchange mode in mirrors. Convective effects and correlation with experiments will be discussed.

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STUDY OF THE EFFECT OF LOCALIZED ECH ON TRANSPORT AND STABILITY IN PLASMAS*

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The ray tracing code TORAY [1] has been linked with transport codes in order to model electron cyclotron heating in PDX [2]. Simulation studies have been carried out using two different transport codes -- BALDUR [3], a 1-d predictive transport code, and TRANSP [4], an analysis transport code that uses available diagnostic data. The results of the BALDUR-TORAY simulation are consistent with the assumption of no degradation of confinement during the ECH phase of the discharge when the electron cyclotron resonance is located at the center of the plasma as well as when it is located away from the center. The sensitivity of the expected heating, to variations in the model for χ_e and to changes in the location of the ECH resonance, is examined using the BALDUR-TORAY simulation. Resulting temperature and density profiles are compared with electron cyclotron emission and Thompson scattering measurements. In the TRANSP-TORAY simulation studies, diagnostic data taken during the PDX-ECH experiments are used as input, and the computation yields the power balance and associated transport coefficients that are consistent with the experiment. Details of the TRANSP-TORAY studies will be presented. The simulation studies confirm the localized nature of ECH which indicates the possibility of controlling energy transport at the plasma center by localized heating or current drive. For example, suppressing the $m=1$ mode, and the associated island that forms in the central region of the plasma might improve confinement in this region. Similarly, deposition of ECH power in the $m=2$ island near the plasma edge may improve overall confinement and minimize disruption. Conditions required for accomplishing localized ECH in PLT are examined.

*Supported by DoE Contract Nos. DE-AC02-76-CHO-3073 and DE-FG02-84-ER5-3187 and by the CUNY Faculty Research Award Program.

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Analytic Mirror Equilibria with New Long-Thin Terms*

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An analytic equilibrium for a tandem mirror with quadrupole symmetry is derived. We simultaneously expand in β (plasma pressure / magnetic pressure) and λ (long-thin parameter) using a maximal ordering so that both effects enter competitively. These new long-thin corrections extend the results of Pearlstein, et al.¹, and can be shown in some cases to be the dominant terms. The new terms make the flux surfaces more diamond shaped than previously thought, and change the scaling of the flux surface distortions with β . Using model pressure and field profiles, simple analytic expressions for the new corrections and flux surface are found and compared with the results of the VEPEC 3D equilibrium code.² For the Constance mirror we find good qualitative and quantitative agreement for flux surface shapes and β scaling.

*Performed by MIT for the U.S.D.O.E under contract DE-AC02-78ET51013

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LOW-n TOKAMAK RIPPLE TRANSPORT, AND ITS EFFECT
ON ROTATIONAL DAMPING*

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Previous theories of ripple-induced transport in tokamaks¹⁻³ have assumed that n , the toroidal periodicity number of the ripple perturbation, was large ($n \gtrsim 10$), corresponding to the number of toroidal field coils. We have generalized the ripple transport coefficients to allow for $n \sim 1$, as well as permitting the ripple perturbation to have a time dependence $\exp(-i\omega t)$. Significant ripple perturbations of this type may arise either from external field errors of lower periodicity than the number of TF coils (for which $\omega = 0$), and also from low- n MHD modes generated by the plasma itself. Because n is small, a rather small amplitude perturbing field can shift the flux surfaces an appreciable amount, causing a significant ripple amplitude δ along a field line; for both the externally and internally-induced perturbations, δ of order a percent is a reasonable value. For the same δ , the low- n induced transport can be large compared with that from the usual high- n perturbations, for some collisionality regimes of interest. The larger toroidal torque arising from this enhanced radial transport may provide an explanation for the anomalously rapid equilibration rate of toroidal rotation in response to the application or cessation of neutral beams, observed in tokamaks such as TFTR and ISX.

¹R. Linsker and A.H. Boozer, Phys. Fluids 25, 143 (1982).

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NUMERICAL COMPARISON OF STRONG LANGMUIR
TURBULENCE MODELS

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Two models of strong Langmuir turbulence are the Zakharov equations

$$i\partial_t E(x,t) + \partial_x^2 E = nE \quad ,$$

$$(\partial_t^2 - \partial_x^2)n(x,t) = \partial_x^2 |E|^2 \quad ,$$

and the nonlinear Schroedinger equation

$$i\partial_t E(x,t) + \partial_x^2 E + |E|^2 E - WE = 0 \quad ,$$

which can mathematically be obtained by dropping the time derivative term from the second Zakharov equation; W is the spatial average of $|E|^2$. One interesting physical situation is modelled by a zero-wavenumber pump mode which is either large initially or which grows exponentially due to an external source of energy. Small perturbations grow exponentially due to modulational instability which saturates nonlinearly via the formation of solitons. The two models are solved numerically and the results are compared with each other and with the soliton gas model¹ of strong turbulence.

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1985 Sherwood Theory Conference; April 15-17, 1985; Madison, Wisconsin

A ONE-DIMENSIONAL THEORY FOR LOWER HYBRID CURRENT DRIVE *

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Conventional 1-D treatments of lower-hybrid current-drive assume a Maxwellian distribution in the perpendicular direction. However, 2-D Fokker-Planck calculations [1] show that the pitch-angle scattering of particles leads to a perpendicular temperature in the plateau region that is significantly enhanced over the bulk temperature. Further, these calculations also show that the quasilinear plateau is enhanced over that given by 1-D theory. For this reason a simple one-dimensional Fokker-Planck equation does not give satisfactory results. We extend here a model [2] in which we take into account two moments of the distribution with respect to the perpendicular velocity, namely $F(v_{\parallel}) = \int_0^{\infty} v_{\perp} f(v_{\perp}, v_{\parallel}) dv_{\perp}$ and $\phi(v_{\parallel}) = \int_0^{\infty} v_{\perp}^3 f dv_{\perp}$. When moments of the F.-P. equation are taken, the equation for ϕ involves the higher moment $\int_0^{\infty} v_{\perp}^5 f dv_{\perp}$, and some closure assumption is necessary.

From the 2-D numerical results it is clear that the effect of the rf spectrum is not confined to the region of $v_{\parallel}$ in which it falls, but that high energy particles are pitch-angle scattered back to lower $v_{\parallel}$. At values of $v_{\parallel}$ below the plateau the distribution may be expected to consist of a central cool Maxwellian plus a tail of hot particles originating in the plateau. For such a distribution the closure assumption $\langle v_{\perp}^4 \rangle = 2 \langle v_{\perp}^2 \rangle^2$, which is exact for a Maxwellian, is not likely to be very accurate. The essential new step in our theory is to recognize this, and to write the distribution function as $f = f_0 + f_1$, with f_0 the initial Maxwellian, then deal with moments of f_1 and apply the closure assumption to them. Numerical solutions of the resulting one-dimensional equations indicate that they are capable of accurately reproducing the main features of the 2-D solutions, namely $F(v_{\parallel})$ and $T_{\perp}(v_{\parallel}) = \phi/2F$.

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2. K. Hizanidis, V. Krapchev, and A. Bers, in *Proceedings of the Fifth Topical Conference on Radio Frequency Plasma Heating*, 21-23 February 1983, p. 160, University of Madison, Madison, Wisconsin.

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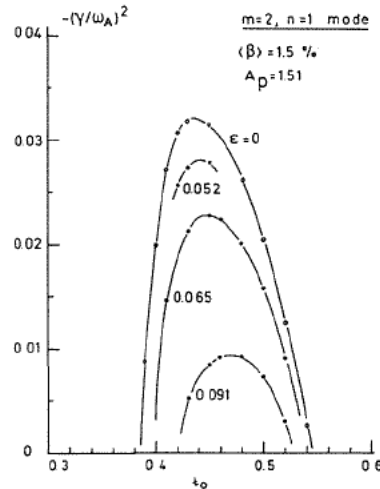
Effect of Shear and Torus Curvature on $m = 2$ Modes in $\ell = 2$ Stellarator Configurations

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The stability of straight and toroidal $\ell = 2$ stellarator configurations with negligible net current has been investigated against internal $m = 2$ modes by using the asymptotic code by Johnson et al.¹ (results are reported below) and the fully three-dimensional code BETA by Garabedian et al.² (results will be presented at the conference). The equilibrium configurations are characterized by the helical aspect ratio of a field period, $A_P = L_P/2\pi a = 1/ha$, a parabolic pressure profile in the minor radius r of the flux surface contours ($\beta(r) = \beta(0)(1 - \psi)$, ψ is the normalized poloidal flux being zero at the magnetic axis, a is the minor radius of the surrounding conducting wall, $\langle\beta\rangle \approx \beta(0)/2$), the rotational transform $t(0.4 < t(0) < 0.6$), and the number of field periods $M = 5$ (as in the W VII-A device). In the present model the $\ell = 2$ equilibrium configurations are described by Bessel functions (Bessel model). The longitudinal wave number $ka = ha/M$ is kept fixed while the helical aspect ratio A_P and the toroidal aspect ratio $A = R_T/a = 1/\epsilon$ are varied. In computing the normalized eigenvalues $(\gamma/\omega_A)^2$ the profile of the equilibrium mass density is assumed to be $\rho = (p/p(0))^{1/2}$, $(\omega_A = v_A/R_T, v_A = (B_0^2/\rho_0)^{1/2})$ is the Alfvén velocity; for numerical calculations $B_0 = 1, \rho_0 = 1, R_T = 1$ is assumed). In case of straight $\ell = 2$ configurations of long period length L_P the shear is small ($t(r) \approx t(0)[1 + (hr)^2/2 + \dots]$, $ha = 0.25$ as in W VII-A) and no shear stabilization of the unstable $m = 2$ mode can be observed. At $ha = 0.65$ the shear increases to $\Delta t/t(0) \approx 0.22$ and the most unstable $m = 2$ mode is stabilized only for values of $\langle\beta\rangle \leq 0.3\%$ being small. Furthermore it is shown that the maximum of the eigenvalue curve scales like $(\gamma a/v_A)^2 \sim \langle\beta\rangle(ha)^2$ which coincides with analytical results based on the stellarator expansion.

The effect of the torus curvature ϵ is demonstrated in Fig.1. The eigenvalues of the unstable $m = 2$ mode are shown as function of the rotational transform t_0 at magnetic axis for $\epsilon = 0$ and no vertical field (corresponding to the straight case) up to $\epsilon = 0.091$. In this parameter study a fixed vertical field of $B_v/B_0 = 0.015$ is used for $\epsilon \neq 0$ to compensate for the global radially outward shift of the plasma column at finite β . The maximum of the eigenvalue curve decreases and is shifted to the right as the torus curvature ϵ increases. For $\epsilon > 0.11$ this mode is stabilized.

Fig.1: Eigenvalue versus rotational transform t_0 at various values of the torus curvature ϵ .



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Injection of Large Pellets in TFTR: Theory Issues*

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Injection of large pellets ($\Delta\bar{n}/\bar{n} \geq 1$) into neutral beam heated TFTR plasmas is planned for late March and early April 1985. The electron temperature is significantly higher ($T_e(0) \simeq 3-4$ keV) than that encountered by pellets in earlier experiments on other devices while the beam energy in these first experiments will be comparable to that in D-III pellet injection experiments ($E_0 \simeq 70-80$ keV). The main issues to be resolved by these experiments are: 1) how does the large mass perturbation affect the plasma on both short and long timescales; and 2) how far do the pellets penetrate into the plasma with its higher electron temperatures and fast ion heat fluxes, i.e., is the ablation model used for simulating earlier experiments still adequate?

The short-time plasma response to a large mass perturbation depends on the penetration depth. The largest pellets are expected to penetrate to or beyond the magnetic axis, so these pellets may not resolve the question of rapid mixing inside the $q = 1$ region. The long-time plasma response is primarily governed by the density decay, which is limited by recycle, and the possibility of triggering disruptions.

Penetration of large pellets is greatly enhanced by plasma cooling during the ablation process, or 'self-limiting' ablation. The fundamental assumption in current models for self-limiting ablation is that the electrons remain Maxwellian, i.e., that the electron-electron collision timescale is short compared to the time for the pellet and its surrounding cloud to pass through a flux surface. In TFTR plasmas this assumption is not generally valid so models are being examined which include an approximation to the time-dependent electron Fokker-Planck equation.

The assessment of fast ion effects hinges on the degree to which the pellet cloud is ionized. Neutral cloud models predict greatly enhanced ablation from fast ions, whereas fractional ionization of 10-20% greatly increases attenuation of fast ions in the cloud and therefore reduces the ablation of the pellet surface.

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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

**Elimination of the Stabilizing Effect of Finite
Larmor Radius on Ballooning Modes in Tokamaks and Tandem Mirrors****M. Kotschenreuther and H.L. Berk*

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Ballooning modes (without electron dissipation) have been examined analytically in tokamaks and tandem mirrors including parallel thermal ion dynamics. The latter can lead to the elimination of the stabilizing influence of finite Larmor radius (specifically ω_*). Modes which would be stable neglecting parallel dynamics can, in some regimes, have growth rates comparable to or exceeding the MHD values. With equilibrium temperature gradients, the instability threshold can be reduced below the MHD case. The general degree of destabilization is determined by the strength of coupling to ion sonic and thermal effects, which arise even in ideal, compressible MHD. For the tokamak case, these are very strong in the region within $\sim 20\%$ of marginal stability, a region of current experimental relevance. An analytic dispersion relation is derived in this regime for the ideal MHD case; it is shown that the expansion energy is not carried by the perpendicular inertial, but by sonic kinetic energy production and compression. Extension of the analytical techniques to both fluid and kinetic regimes with ω_* reveals the destabilizing effects stated above. With ion temperature gradients, the Alfvén continuum can be destabilized (an ion ω_* mode) leading to possible instabilities well below the MHD threshold. A solely kinetic formalism is used for tandem mirrors; the magnitude of the effects from parallel ion motion depends on the variation of field strength along field lines. With a choke coil, they are substantial for all β values above ideal marginal stability.

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PARALLEL VISCOSITY IN A TANDEM MIRROR*

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It appears that the imposition of conservation of parallel momentum may be important in the determination of the azimuthally varying parts of the electrostatic potential (which drive a radial $\vec{E} \times \vec{B}$ flux) in a tandem mirror.¹ This effect is implicitly ignored in most tandem mirror transport calculations through the use of non-momentum conserving collision operators. Inclusion of momentum conserving operators makes a kinetic analysis quite difficult. The moment approach, however, includes momentum conservation naturally, without requiring the detailed form of the collision operator. The success of the method depends on the kinetic determination of the higher order moments (parallel and azimuthal viscosity) in terms of the lower order moments (e.g., flow velocities).

Presented here is a calculation for the parallel viscosity in a tandem mirror. Using a momentum conserving model collision operator,² the parallel viscosity can be shown to damp parallel flows with a coefficient inversely dependent upon the fraction of "passing" particles (i.e., those particles which pass into regions of large geodesic curvature). The effects of this viscosity on parallel momentum balance and the determination of the ambipolar potential will also be discussed.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy under contract DE-AC02-80ER53104 with the University of Wisconsin.

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Heat Transport by Electrostatic Microturbulence in the Edge
Regions of the Caltech Research Tokamak*

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Extensive measurements of the microturbulence in the edge regions of the Caltech Research Tokamak allow a unique comparison of the heat transport resulting from three basic turbulent mechanisms: (1) heat transport due to the particle flux caused by microscopic electric field fluctuations; (2) thermal conduction due to microscopic electric field fluctuations; and (3) thermal conduction due to microscopic magnetic field fluctuations. These measurements include determination of the particle flux induced by poloidal electric field fluctuations[1,2]; determination of the level of microscopic magnetic fluctuations $\tilde{B}_r/B$ [3]; and determination of an upper limit on the electron temperature fluctuations $\tilde{T}_e/T_e$ [4]. The results indicate that, in the edge regions, the electron heat transport due to the measured turbulence-induced particle flux is comparable or greater than that due to the thermal conduction caused by electric field fluctuations and is significantly greater than due to the measured magnetic fluctuations. The resulting edge electron energy confinement time is estimated to be comparable to the global energy confinement time of ~ 1 ms.

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Eigenmode Structure and ICRF Heating and Stabilization of Axially Symmetric Systems

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RF electric fields play an important role in plasma heating and stabilization of MHD modes in the PHAEDRUS Tandem-Mirror Experiment [1]. For both purposes the knowledge of the radial behavior of electric fields is of importance. We use a cylindrical, cold fluid plasma model [2,3] to calculate the radial profiles of E^+ and E^- and to determine the regimes of propagation. Using the fluid model to calculate the ponderomotive force due to an arbitrarily polarized electric field [4], we find that this model does not adequately describe the experimental results. It appears that near-field and surface effects may be important.

Supported by United States Department of Energy Contract DE-AC02-78ET51015

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SHERWOOD THEORY MEETING 1985
 Madison, Wisconsin
 April 15 to 17

**Finite Ion-Gyroradius Corrections to the
 Toroidal Tearing Mode***

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Linear drift-tearing instability, with ion-gyroradius effects, in large aspect ratio tokamak plasma is investigated, using a self-consistent, energy-conserving reduced fluid model.¹ The "boundary-layer ordering"² $—wk_{\perp} \ll 1$, (where w is the radial width of the boundary layer and $k_{\perp}$ is the perpendicular wave vector) is used to analyze the layer-interior equations and compute the critical value of Δ' .

The ion temperature is allowed to be comparable to the electron temperature, but temperature gradients and particle trapping effects are omitted for simplicity.

¹C.T. Hsu, R.D. Hazeltine, and P.J. Morrison, IFSR #171 (1985).

²R.D. Hazeltine and J.D. Meiss, to be published in Physics Reports.

[†]Also Department of Physics.

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

Local Power Conservation for Linear Wave Propagation in an Inhomogeneous Plasma, R. SUND, J. SCHARER, AND B. McVEY, University of Wisconsin [1], Madison, Wisconsin and Los Alamos National Laboratory [2], Los Alamos, New Mexico -- An expression for local power absorption in a non-uniform, hot magnetoplasma is derived from fundamental principles. The definition is developed under the assumptions of the Vlasov theory of plasma waves. We obtain

$$P(\vec{r}) = \int d^3v < \vec{E}(\vec{r}', t') \cdot \vec{v}' f_1^*(\vec{r}', \vec{v}' t') >$$

where the primed variables define the unperturbed particle trajectories with $\vec{r}'(\vec{r}, \vec{v}, t') = \vec{r}$ and $\vec{v}'(\vec{r}, \vec{v}, t') = \vec{v}$ at $t' = t$, and the brackets denote an average over t' . The definition of P allows a unique identification of the terms in a local power conservation relation. It is this uniqueness which distinguishes our approach from previous attempts. The formalism is applied to time-harmonic waves propagating in a plasma in which the magnetic field, particle density and temperature vary in one dimension transverse to the magnetic field. We show a systematic procedure whereby one may write P in the form

$$P = \vec{E} \cdot \vec{J}^* - dS/dx$$

where S is the kinetic flux. This is used in conjunction with Maxwell's equations to write the conservation relation. Correctness is verified by an independent calculation of $\vec{J}$ as the first velocity moment of the perturbed distribution function. Expressions for power absorption, kinetic flux, and current density are presented. They are correct to second order in a gyro-radius expansion of the wave field and to first order in the scale lengths of B , n , and T and therefore applicable to the ion cyclotron range of frequencies. They remain applicable in strong damping and mode conversion regimes. Further support is provided by a calculation of the conservation relation for a single wave mode in a uniform plasma. The expressions are shown to reduce to the correct weak damping limit. Finally, a numerical procedure for solving the wave equations governing propagation in the non-uniform plasma is described. Field solutions, power flux and the local power absorption by each particle species is presented for examples in the fast wave - ion Bernstein mode conversion regime.

[1] Supported by NSF Grant ECS-8212173.

[2] Supported by DOE Contract DE-AC02-78ET51013.

NEOCLASSICAL TEARING INSTABILITIES IN TOKAMAKS*

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Recently, it has been realized^{1,2} that the resistive MHD model usually adopted in analysis of fluidlike plasma instabilities, although quite good in the direction perpendicular to magnetic surfaces, is inadequate along magnetic field lines for plasmas in which the mean free path is greater than the connection length. Since most present tokamaks operate in this regime, it is natural to reexamine the dominant instabilities with the long mean free path influence taking into account.

Starting from a resistive MHD set of equations with neoclassical effects (such as bootstrap current, neoclassically enhanced ion polarization drift current, and a pinch force type current caused by the pressure perturbation gradient along field lines) included, we derive and solve the eigenmode equation and the dispersion relation for tearing instabilities. In doing so, we utilize a ballooning mode representation, a multiple length scale approximation and a variational approach to finding the instability eigenvalue.³ The results show that the long mean free path influence on tearing modes is quite strong, especially for $\sqrt{\epsilon} \beta_p \gg S^{-2/5}$ (ϵ is the inverse aspect ratio and β_p is the poloidal beta value). Typically, for $\sqrt{\epsilon} \beta_p \sim 1 \gg S^{-2/5} \sim 10^{-2}$, it is found that $\gamma \propto S^{2/3}$, $\delta x \propto S^{-1/3}$ where γ , δx , and S are the growth rate, the width of the singular layer and the "neoclassical" magnetic Reynolds number, respectively.

-
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MHD MODELLING WITH THE HALL TERM

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J. N. Leboeuf (Institute for Fusion Studies)

F. Brunel (National Research Council of Canada)

J.M. Dawson (University of California, Los Angeles)

Most fluid calculations for fusion plasmas are done by conventional MHD models. It is desirable to construct fluid models which contain more physics. We have begun a program of building a fluid model which contains the Hall term in Ohms Law. This is an extension of the earlier work by T. Tajima, J.N. Leboeuf, J.M. Dawson (J. Comput. Phys. 38 (1980), 237). We are using the same particle fluid approach used by F. Brunel, J.M. Leboeuf, T. Tajima, J.M. Dawson (J. Comput. Phys. 43 (1981), 268). Our goal is to construct a 3-dimensional model suitable for examining the influence of the Hall term to wave propagation and stability. To date we have been generalizing the earlier 2-1/2 dimensional work of Tajima, Leboeuf, Dawson to include arbitrary angles of propagation. The model exhibits acoustic, magnetoacoustic, Alfven, ion cyclotron, and whistler waves. The simulation results are compared to analytic dispersion relations.

NONLINEAR RADIAL PROPAGATION OF DRIFT WAVE TURBULENCE

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By solving the model nonlinear equation of collisional drift wave turbulence,¹

$$\left(\frac{\partial}{\partial t} - \nabla \phi \times \hat{z} \cdot \nabla \right) \nabla^2 \phi = \bar{C}_1 (\phi - n) + C_2 \nabla^4 \phi$$

and

$$\left(\frac{\partial}{\partial t} - \nabla \phi \times \hat{z} \cdot \nabla \right) (n + \ln n_0) = \bar{C}_1 (\phi - n) ,$$

where

$$\bar{C}_1 = - \frac{T_e}{e^2 n_0 \eta \omega_{ci}} \frac{\partial^2}{\partial z^2} , \quad C_2 \equiv \frac{\mu}{\rho_s^2 \omega_{ci}} ,$$

$$e\phi/T_e \equiv \phi, \quad n_1/n_0 \equiv n, \quad \omega_{ci}t \equiv t \quad \text{and} \quad x/\rho_s \equiv x ,$$

for mixed initial and boundary values, radial propagations of the drift wave turbulence is studied. It is found that the turbulence propagates radially, in the direction of decreasing resistivity, through the nonlinear mode couplings.

¹ A. Hasegawa and M. Wakatani, Phys. Rev. Lett. 50, 682 (1983), Phys. Fluids 27, 611 (1984).

ANALYTICAL STUDY OF ENERGETIC IONS SLOWING
DOWN IN PLASMAS*

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ABSTRACT

Energetic ions, such as fusion products or ionized neutral beam ions, slow down by coulomb collisions with the background plasmas depositing their energy into the plasma. The slowing down problem has been considered by many authors. However, the analytical solutions have been limited to the fast ion velocity range $v_i \ll v \ll v_e$ where v_i and v_e are respectively the ion and electron thermal velocities. A new analytical solution without this limitation, valid over the entire velocity range is worked out. It is shown that the distribution function of the energetic ions can be written as an asymptotic series in $\epsilon \equiv T_e/E_a$ where T_e is the electron temperature and E_a is the birth energy of the fast ions. The power transfer from the energetic ions to the plasma species are calculated. Collisions with the energetic ions can cause the background ion distribution to depart from a Maxwellian and may result in fusion reactivity enhancement. However, this effect has been found to be negligible in most cases. The analytical work has been compared with numerical calculations and excellent agreement has been found.

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STELLARATOR EXPANSION STUDIES OF HELIOTRON-E*

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The stellarator expansion predictions for the stability properties of Heliotron-E agreed well with earlier experimental measurements¹ for $\langle\beta\rangle \sim 1.5\%$. Operation at $\langle\beta\rangle \sim 2\%$ has been reported recently.² Since these β 's are well above the analogous Troyon limits observed in tokamaks,³ we have attempted to raise the calculated critical β 's by changing the shape of the pressure distribution. Introduction of a pressure profile with $dp/d\Psi = 0$ at both the magnetic axis and the plasma boundary into the code enables us to flatten the pressure at the $\chi = 1$ surface. Studies of surface structure using both Poincaré plots and Hamiltonian techniques⁴ indicate that, because of the large shear, significant island structure should not be observed at $\langle\beta\rangle \lesssim 2\%$ even near the $\chi = 1$ surface. As we flatten the pressure at the $\chi = 1$ surface, we see the growth rates for all the $n/m = 1$ modes, that had been centered at this surface, decrease dramatically. However, an $n = 3, m = 2$ mode grows at the $\chi = 1.5$ surface. Although we could stabilize this $n = 3, m = 2$ mode by flattening the profile locally, it is clear that higher- n modes would rise to take its place. Also, the critical β for ballooning is increased only slightly. It appears that critical $\langle\beta\rangle$'s above about 1.5% would be hard to achieve. This suggests the possibility that stellarators without ohmic current may have better experimental stability properties with respect to theory than analogous tokamaks do.

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[†]On loan from Westinghouse R&D Center.

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²K. Uo and Heliotron E Team, 5th International Workshop on Stellarators (Schloss Ringberg, FRG, Sept., 1984) Vol. 1, p. 17 and 113; K. Uo *et al.*, Nucl. Fusion 24, 1551 (1984).

³F. Troyon, R. Gruber, H. Saurenmann, S. Semenzato, and S. Succi, Plasma Physics 26, 1A, 209 (1984).

⁴A.H. Boozer, Phys. Fluids 26, 1288 (1983).

Investigations of Long-Thin Mirror Equilibria with the Full 3-D
Method as Computed by VEPEC

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Recently MHD equilibria have been computed for existing and projected machines using equilibrium codes exploiting the long-thin geometry of these machines. Through a new algorithm, due to McNamara, the large number of iterations needed for convergence has been reduced from roughly 10,000 to 20. We compare the results of such a long-thin code, developed by Pearlstein and co-workers, with the 3-D VEPEC code. We wish to ascertain:

- (a) Do both codes converge to the same solution for a long-thin geometry?
- (b) Are the slow convergence problems of earlier long-thin codes also found in the VEPEC code?
- (c) At what point does the long-thin approximation lead to substantial errors?

We will address these questions by comparing previous results computed for a modified 2XIIB coil set which satisfies the long-thin approximation for "pencil" shaped plasmas with the VEPEC results for the same coil set. The mirror ratio enhancement and the mid-plane equilibrium flux surface displacements are the primary results we compare. The Constance coil set will be used in a further study in which the plasma radius will be varied such that we can explore equilibria with very small aspect ratios (long-thin) to ones with near unity aspect ratios (short-fat). By examining the errors introduced by the departure from a long-thin geometry in a single cell we estimate the errors introduced for the tandem case in which the long-thin solenoidal cells are linked to transition and anchor cells that are often not long-thin.

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Heat Pulse Propagation On TFTR*

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ABSTRACT

Analysis of data from the soft ex-ray array and the acanning ECE electron temperature diagnostic show that the propagation of the saw-tooth induced heat pulses appears diffusive. The pulses propagate much faster than predicted by analytic and numerical solutions of the heat pulse diffusion equation using values of x_e obtained from transport codes. Profile, chord averaging and other effects have been considered and do not significantly affect this result.

Scans have been used to obtain the scaling of x_e with n_e , I_p and minor radius. Some models will be presented which could explain the discrepancy between the values of x_e obtained from transport codes and those obtained from analysis of the heat propagation.

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Effects of Turbulent Density Fluctuations on Neutral Transport*

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Turbulent plasma density fluctuations, such as those observed in tokamak edge plasmas ($\tilde{n}/n \sim 20-80\%$; see Ref. 1 and references therein) will effect the transport of neutral particles in the plasma. Density fluctuations effect the transport by causing fluctuations in the cross sections for ionization and charge exchange for neutrals, which both depend (linearly) on the plasma density $n(r,t)$. Changes in the calculated neutral density profile in a tokamak would lead directly to changes in the calculated energy losses by convection.

Estimates of the size of this effect have been found by solving simple one-dimensional model equations for the neutral density profile with the effects of charge exchange neglected. In the simplest case, homogenous, Gaussian fluctuations in space only [$\tilde{n}=\tilde{n}(x)$] are assumed. The resulting stochastic nonlinear equation can be solved exactly for the steady state neutral density profile. Results indicate that the neutral decay length is increased substantially relative to the deterministic result, λ_e , by roughly a factor of $(1-K_1)^{-1}$ where $K_1 = |\tilde{n}/n|^2 L_c / \lambda_e$ is the Kubo number, L_c is the correlation length of the density fluctuations, and λ_e is the electron impact ionization mean free path. Results from more sophisticate models including such effects as charge exchange will also be discussed.

1. P.C. Liewer, "Review: Measurements of Microturbulence in Tokamaks and Comparisons with Theories of Turbulence and Anomalous Transport" (To be published in Nuclear Fusion).

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RUNAWAY OF RUNAWAY DISCHARGES THROUGH AVALANCHING

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Earlier calculations^{1,2,3} of the rate of runaway electrons in plasmas with DC electric fields F mainly considered the generation of electrons with energies E larger than the critical Dreicer energy $E_c = F\lambda$ being the mean free path of the electrons at E_c . However, the runaway electrons in turn will collide with the thermal electrons and thus by "avalanching" generate secondary electrons which add to the runaway generation rate. In a recent paper,⁴ we obtained a sizable generation of superthermal electron tails in plasmas containing "fast" particles even for quite small density ratios $n_f/n_p \sim 10^{-4}$. Considering secondaries generated during the full lifetime of the original runaways, we now find that a sizable enhancement of the runaway rate will occur even for quite small runaway densities, in particular, in situations with small Dreicer field parameters. Above a critical runaway density n_{fc} the runaway rate then will grow exponentially through such avalanching. Applying the results to various experiments where runaway electron were measured, we find that avalanching may have occurred.

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2. Gurevich, A. V., and Z'hivlyuk, Y. N., Sov. Phys. JETP 22, 153 (1966).
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Lagrangian Variational-Principle Derivation
of a General Theorem for Beat-Resonant Mode Coupling,
with Application to Global Modes of a Nonneutral Plasma*

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For two modes (I, II) interacting via Vlasov beat resonance, we have obtained the mode-action transfer rate:

$$dJ_I/dt = -dJ_{II}/dt = \int d^3I \sum_{\underline{q}} |\tilde{K}_{\underline{q}}(\underline{I})|^2 \underline{q} \cdot \partial f_0 / \partial \underline{I} 2\pi \delta(\omega_B - \underline{q} \cdot \underline{\omega}(\underline{I})),$$

where J_I, J_{II} are the mode actions, $f_0(\underline{I})$ is the unperturbed oscillation center distribution in particle-action space, $\omega_B = \omega_I - \omega_{II}$ is the beat frequency,

$\underline{\omega}(\underline{I}) = \partial H_0 / \partial \underline{I}$ is the particle frequency-vector, and $\tilde{K}_{\underline{q}}(\underline{I})$ is the particle-angle Fourier transform of $\tilde{K}(\underline{I}, \underline{\theta})$, the coefficient of the beat-phase term in the oscillation-center Hamiltonian. This result was obtained by the use of the Lie-transformed Lagrangian action principle [1],

which yields an explicit expression for the coupling coefficient $\tilde{K}_{\underline{q}}$,

which will be displayed. We note that the appearance of its absolute square follows naturally from the Lagrangian variational principle.

This approach was motivated by the problem of beat-resonant coupling of global electrostatic modes in a bounded single-species plasma confined by axisymmetric fields. Recent experiments indicate that a small asymmetry in the field is an important factor limiting the confinement time. Beat-resonant coupling between a field error and a mode is a mechanism whereby such asymmetry may transfer angular momentum to the plasma and thus allow radial expansion [2]. Our formalism is illustrated by a detailed discussion of the coupling in such a single-species plasma.

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LOWER HYBRID WAVE SCATTERING BY RANDOM DENSITY FLUCTUATIONS
IN INHOMOGENEOUS PLASMAS*

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ABSTRACT

In a recent paper,¹ we studied a model for lower hybrid wave scattering by random density fluctuations in homogeneous background plasmas. We extend now our analysis in order to include inhomogeneity in the density profile of the background plasma. A slab of stochastic plasma is considered near the edge plasma-vacuum, where random fluctuations of the density n and of ∇n are superimposed to a certain deterministic profile, while the bulk of the plasma is assumed to be cold and homogeneous. Similar to the case studied in ¹, it is shown that the complex-valued reflection coefficient, $R(L)$, as a function of the slab thickness, L , satisfies a Riccati (stochastic) differential equation, associated with an initial-valued problem, while the original formulation requires solving a (stochastic) two-point boundary-value problem for the electrostatic potential. Then the mean transmitted and reflected power, $\langle |R|^2 \rangle$, can be evaluated as a function of L , by numerical simulation from the Riccati equation above. New phenomena appear with respect to the previously studied model,¹ such as (internal) refraction besides the reflection due to the random scatters.

¹W. Grossmann and R. Spigler, "A stochastic model for lower hybrid wave scattering by density fluctuations," to appear in Phys. Fluids.

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RELAXATION OF FINITE BETA TOROIDAL PLASMAS

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Equilibria with minimum energy are constructed from a variational principle¹ in which the potential energy of a plasma is minimised subject to a small set of global invariants. Recent work², in which we have constructed low q tokamak equilibria (with zero current on the boundary) which are ideally and resistively stable, is now extended to include finite pressure. The pressure profiles, which have nonzero gradients, are prescribed uniquely by the inclusion of specific global invariants in the variational principle. These "invariants" are preserved exactly by ideal notions of the plasma and approximately by a tearing mode of the $m=1, n=1$ type. Estimates of the decay rates for the energy and the invariants are given, and shown to be consistent with our conjectures on selective decay. Results on the tokamak window as well as the transition region between the tokamak and RFP windows, relevant to the recently proposed Wisconsin experiment, will be presented. The stability of the relaxed states with finite pressure are presently under study. It is argued that the present approach may be useful for computing MHD equilibria for stellarators with imperfect flux surfaces³.

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Derivation of Scaling Laws for Trapping Rates
of Passing Ions in a Mirror Cell*

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Maintenance of a thermal barrier and MHD stability in tandem mirrors requires continual pumping of ions that become trapped in the end cells. In order to know how fast to pump these trapped ions, it is necessary to ascertain the rate at which they are being trapped. Results from the two-dimensional, nonlinear, multispecies Hybrid-II code, which uses the square-well approximation¹, are presented. The equations solved are $(\partial f_a / \partial t)_{FP} = \nu_a f_a$ subject to the boundary condition $f_a = f_a^{\text{pass}}$ at the trapped/passing separatrix in velocity space. Here f_a is the distribution function of trapped species a and ν_a is the pumping rate (taken to be independent of velocity). The distribution function of passing particles f_a^{pass} is taken to be a Maxwellian of given density and temperature. The mirror ratio and potential are specified, along with the quantity $g_a = 1 + n_a/n_a^{\text{pass}}$.

The cases presented here consider only a single ion species. Deviations of the trapping coefficient ν from the previously assumed² scaling are observed; most importantly, ν is seen to increase faster than $Z_m^{-1/2}$. The quantity ν can be expressed as

$$\nu = \frac{Z^4 \ln \Lambda}{T_p^{3/2} m^{1/2}} n y(R, \bar{\phi}, g),$$

where T_p is the temperature of passing ions, $\bar{\phi} = Ze\phi/T_p$ and the function y is to be determined. Fits of y (and hence ν) accurate over a wide range of R , $\bar{\phi}$ and g are presented.

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

²A.H. Futch and L. LoDestro, LLNL Report UCRL-87249 (1982)

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ELECTRON DISTRIBUTION FUNCTIONS PRODUCED BY HIGH POWER ECRH

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High power electron cyclotron resonance heating is capable of producing substantially non-Maxwellian electron distributions. Such distortions may generate pressure anisotropy, affect wave propagation and absorption, change current drive efficiency calculations and modify the interpretation of data from X-ray, Thomson scattering and electron cyclotron emission diagnostics. Some of these effects have already been observed during low density experiments on the TOSCA and CLEO tokamaks¹.

Theoretical studies of these phenomena have been carried out using a 2-D non-linear Fokker-Planck code. The Fokker-Planck equation is bounce averaged to take account of particle trapping and incorporates the ohmic heating electric field and a particle-conserving energy loss term. The wave-particle interaction term is calculated using a single particle model akin to that of Cairns and Lashmore-Davies². This approach allows us to treat, in a physically transparent way, the finite size of the RF beam, the variation of the cyclotron frequency along the magnetic field lines, the attenuation of the wave and the heating of electrons out of resonance (due to the relativistic mass dependence on energy) before they can completely cross the RF beam.

The code has been used to simulate the soft X-ray emission spectra observed from both weakly and strongly distorted electron distributions produced by 60 GHz and 28 GHz second harmonic ECRH experiments on CLEO. Comparisons of theoretical and experimental X-ray spectra will be presented along with results showing the effect of high power on current drive efficiency.

- 1) D C Robinson et al, Proceedings of 10th IAEA Conf on Plasma Physics and Controlled Nuclear Fusion Research 1984, London to be published.
- 2) R A Cairns and C N Lashmore-Davies, submitted to Plasma Physics.

ANOMALOUS TIME BEHAVIOR OF ENTROPY IN A NON-MAXWELLIAN PLASMA*

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The thermal relaxation of a 2-dimensional plasma is investigated by observing the change in entropy. A uniform magnetic field is applied perpendicular to the plane of the simulation. Initially the velocity distribution function $f(v)$ is uniform and cut off at $v = v_0$. From there, it evolves to a Maxwellian $f(v)$. In the simulation $f(v)$ and the entropy S , where $S = -\int f(v) \ln [f(v)] d^2v$, are computed at regular intervals. The time behavior of the entropy for small magnetic field strengths (including $B_0 = 0$) is observed to relax like $\exp(-\sqrt{t}/\tau_0)$ rather than $\exp(-t/\tau_0)$. Cases with large magnetic fields are currently being investigated and seem to exhibit a similar time evolution.

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Modulation of Small Scale Turbulence by Sawtooth Relaxations
in the TEXTOR Tokamak - Observation and Interpretation

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Observation of microturbulence in the TEXTOR plasma by forward scattering of CO_2 laser light has revealed that a periodic enhancement of the turbulence level registered along a central vertical chord precedes and follows the sawtooth relaxations, detected along all the channels, of the line average density and the temperature relaxation, measured on the magnetic axis. The maximum enhancement occurs almost simultaneously with the relaxation on the central density channel. These observations imply that a small perturbation of the line average density ($\sim 2\%$) and of the temperature ($\sim 10\%$) are sufficient to induce a finite ($\sim 50\%$) modification of the turbulence level. In line with the standard interpretation of anomalous electron heat transport, we infer that the electron heat conduction χ_e is, in stationary - or, rather, in periodic, (in view of the sawtooth relaxations) - operating conditions, also a rapidly varying function of these parameters. This conclusion was anticipated elsewhere (A. Rogister et al., Xth IAEA Conference, London 1984, paper E-III-1., G. Hasselberg and A. Rogister, Nucl. Fus. 23, 1351 (1984)). A mathematical model which simulates this feature will be presented and the synthetic signals constructed from the model will be compared to the observations.

Viscosity Tensor and Toroidal Momentum
Confinement of Strongly Rotating Tokamak Plasma

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The full viscosity tensor $\pi = \eta_o \pi^o + \eta_3 \pi^3 + \eta_1 \pi^1$ where the viscosity coefficients $\eta_o : \eta_3 : \eta_1 = 1 : (\omega\tau)^{-1} : (\omega\tau)^{-2}$ and $\eta_o = nT\tau$, is presented for an axisymmetric tokamak with flow velocity $V_\psi = 0$, $V_\theta \sim V_\phi B_\theta/B_\phi$, $V_\phi \equiv R\Omega(\psi, \theta) \sim \mathcal{O}(V_{thi})$, in the collisional regime. Any physics effect giving rise to a poloidal strain $\Omega^{-1} \partial\Omega/d\theta \sim \mathcal{O}(r/R)$ invokes the gyroviscous piece π^3 and produces a perpendicular (i.e. $\nabla\psi$ - directed) viscous loss of toroidal momentum exceeding the Pfirsch-Schlüter result¹⁾ $\eta_\perp = 4\eta_1(1 + 2.31q^2)$, (and ensuing momentum confinement time $\tau_m = a^2/\eta_\perp$) by $\geq$ one order of magnitude. The poloidal dependence of the rotation frequency Ω is coupled to the poloidal dependence of the ambipolar potential $\Phi(\psi, \theta)$ which in turn can be driven by the difference in centrifugal forces of the main ions and impurities and the large poloidal gyroradius of the impurity (or beam) ions. A fully self consistent calculation of $\Phi'(\psi, \theta)$ is in progress. Preliminary comparison with several experiments suggests that this neoclassical multi-ion viscosity theory of strong rotation results in τ_m -values reaching up to observed values τ_m without invoking the large anomaly hitherto assumed necessary.

¹⁾ J.T. Hogan, Phys. Fluids 27 (1984) 2308.

A B S T R A C T

PARAMETER STUDIES OF FLUID MODEL WALL PLASMA FLOWS

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The flow of fluid like plasma to a neutralizing wall is determined by energy transport within the plasma and by the rate of intrainment through ionization of neutrals emitted from the wall. Two quite different numerical models of the same one dimensional physical fluid model have been used to do parameter studies of these flows, (1) a stationary model using an analytic perturbation treatment to obtain asymptotic boundary conditions on the main plasma side, and (2) a time dependent model. These are in good agreement where solutions exist and show the dependence of main plasma Mach numbers on density, temperature, neutral pumping length, and the angle of B with respect to the wall. In particular, Mach numbers increase with decreasing pumping length, density, and temperature until Mach one is reached, after which no stationary solutions exist. This non-existence of solutions is predicted by the analytic calculation of boundary conditions and only occurs when ion thermal conduction is included.

TANDEM MIRROR ELECTRON CONFINEMENT FROM WEAK TO STRONG ECRH*

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A series of numerical studies are presented which calculate the electron confinement time in a magnetic and electrostatic potential well in the presence of electron cyclotron resonance heating (ECRH). Relativistic Monte Carlo and Fokker-Planck codes are used to obtain the results. In the weak ECRH limit, the injected ECRH power heats the bulk of the electron distribution to increasing temperatures, and the confinement time can be calculated from the Pastukhov formula. At higher powers, a tail is formed on the distribution which results in more rapid loss than that calculated using the bulk temperature. In the strong ECRH limit, the bulk temperature becomes larger than confining potential energy. We shall compare the results in this regime with the formula for magnetic mirror confinement only, and a model proposed by Cohen [1] which gives a reduced confinement time.

- [1] R.H. Cohen, Bull. Am. Phys. Soc. 29, 1228 (1984); an accompanying paper, this conference.

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Electron Rate Equations and Potentials in ECRH-Driven Tandem-Mirror End Cells*

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Electron-Cyclotron Resonance Heating (ECRH) plays an important role in determining potentials in the end cells of thermal-barrier tandem mirrors. This paper describes generalizations of previous work on the limits where ECRH is strong¹ or weak² compared to collisions. The present calculations apply to the determination of the potential difference Φ_{pb} between the plug and thermal-barrier regions and the potential of the barrier relative to ground.

The potential Φ_{pb} is determined by the physics of the electrons trapped in the plug potential well. Expressions are derived for the particle and energy fluxes across the trapped-passing velocity-space separatrix in the strong-ECRH limit, from the collisional perturbation to the infinite-ECRH case. The weak-ECRH perturbation to the energy flux is derived following the approach used previously to determine the particle flux. Interpolation formulas are developed to connect the weak- and strong-heating results, thus providing particle and energy rate equations for the trapped electrons applicable at any ECRH level. In the usual limit where the explicit source of trapped electrons is negligible compared to one-way flows across the separatrix, the steady-state version of the particle rate equation yields a relation between Φ_{pb} and the trapped density which approaches the usual Boltzmann-like relation³ in the limit of zero ECRH and the power-law relation of Ref. 1 in the limit of infinite ECRH.

The potential of the barrier or central cell relative to ground is determined from the requirement that the net rates of loss of electrons and ions from a flux tube be equal. In Ref. 2 it was noted that ECRH can enhance electron endloss, and an estimate was obtained from a simple model in which barrier electrons are diffused by ECRH to high energy along a heating characteristic emanating from a low energy, scattered by collisions through a small angle onto a characteristic intersecting the loss cone, and then diffused by ECRH into the loss cone. The model is made somewhat more sophisticated here by (abruptly) dividing the velocity space of electrons passing to the central cell into collision-dominated and ECRH-dominated regions, with the division at energy E_c ; the flux into the loss-cone characteristic is then rigorously derived within the context of the model.

Comparison of these results with Fokker-Planck and Monte Carlo calculations and application in the modelling code TREQ are described in the adjacent papers by Rognlien and Matsuda, and by Gilmore and Rensink, respectively.

* 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 R. H. Cohen, *Phys. Fluids* **26**, 2779 (1983)

² R. H. Cohen, *Bull. Am. Phys. Soc.* **29**, 1228 (1984)

³ R. H. Cohen, I. B. Bernstein, J. J. Dornring, G. Rowlands, *Nucl. Fusion* **20**, 1421 (1980)

SIMULATION OF LOSS OF PLUGGING IN TMX-U USING THE TREQ CODE

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A new set of particle and energy balance equations for the warm, electrostatically confined electrons in the plug region of thermal barrier tandem mirrors¹ has been implemented in the TREQ (tandem rate equations) code. An important feature of the new model is expressions for particle and energy transfer between the warm, hot, and passing electrons which are valid for arbitrary ECRH power levels. We therefore now have the capability to continuously pass from collision dominated regimes to ECRH diffusion dominated regimes and vice-versa, making it possible to attempt to simulate loss of plugging and high density operation in TMX-U. Comparison between experimental data and code simulations will be presented, with emphasis on simulation of loss of plugging, its causes, and its prevention.

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¹R. H. Cohen, this meeting.

CALCULATION OF SLOSHING-ION BUILDUP
IN THE TMX-U END CELL

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We have used SMOKE--a multi-region, bounce-averaged, Fokker-Planck code--to calculate the buildup of sloshing ions in the end cell region of TMX-U. We have modeled the plasma potential, magnetic field and sloshing ion beam profiles that presently exist in the experiment. The effect of the penetration of molecular and Franck-Condon neutrals on the sloshing ion buildup is included. Our calculations show that the thermal barrier depth and the plugging potential that can be achieved in TMX-U are sensitive to the species mix of the 15 keV sloshing ion beams.

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COMPARISON OF PROPOSED IGNITION EXPERIMENTS
AND PLASMA THEORY ISSUES*

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The realization that new physical regimes have to be produced and important collective processes have to be dealt with in order to attain fusion burning conditions, has brought about a strong interest for experiments that are potentially capable of reaching these conditions. A comparative review of three experimental devices proposed in the U.S. - Ignitor (MIT), I.S.P. (Princeton) and E.T. (General Atomic) - is given.

The major unresolved theoretical issues that are of special concern are: a) the excitation of internal modes ($m^0=1$) in the presence of strong α -particle heating of the central part of the plasma column; b) the ion thermal transport resulting from modes driven unstable by the ion temperature gradient.

The frequency at which "sawtooth oscillations" of the plasma column occur has an important influence on the time needed to achieve ignition conditions. This frequency is determined by the threshold of $m^0=1$ reconnecting modes, whose theory, at this time, is limited by the assumption that the width of the produced magnetic island is smaller than the ion gyroradius and therefore is unsuitable to make realistic predictions.

The effects of an anomalous ion thermal conductivity have been taken into account, mostly through an anomaly multiplying factor of its collisional form, in most of the analyses carried out in order to predict the performance of the proposed experiments. On the other hand the possible forms of the effective ion thermal conductivity that can be derived for ion temperature gradient driven modes predict a deterioration of confinement as the temperature increases contrary to the favorable dependence on temperature of the collisional transport. Another important issue is the relationship between the electron temperature and the current density profiles¹ that is related to the form of the electrical resistivity and the influence of trapped electrons on it.

It is pointed that the most relevant experiments to be undertaken are those that allow the investigation of the broadest range of plasma parameters in view of resolving these issues.

*Sponsored by the U.S. Department of Energy

¹L. Sugiyama, "Heating in Igniting Plasmas", abstract submitted to this meeting.

ABSTRACTARE TOKAMAK DISRUPTIONS CAUSED BY MHD
CLUMP INSTABILITY? *

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The MHD clum instability⁽¹⁾ is investigated as a cause of disruptions in tokamaks. It is found that many features of the instability are consistent with observed disruptions. These features include: (1) the triggering by, and the subsequent importance of magnetic field line stochasticity, (2) the onset of the instability before the Kruskal-Shafranov (linear stability) limit is reached, (3) a radial electric field profile characterized by an anomalously large resistivity enhancement in the column center, but a simultaneously smaller and negative electric field (i.e., negative voltage spike) at the plasma edge, and (4) a characteristic voltage spike time scaling with the resistive time (τ_R) and Lundquist number (S) as $\tau_R S^{-\frac{1}{3}}$ over a wide range ($S \sim 10^5$ for LT-3 to $S \sim 6 \times 10^7$ for TFTR). The fundamental non-linear fluctuation characterizing the turbulence is a hole or "bubble" in the current density. Though an individual hole will grow at the rate $\eta_a \Delta' / X_d$ (η_a and X_d are turbulent resistivity and scale length), it will tend to be destroyed by the field line stochasticity. Net growth occurs when turbulent mixing (R) creates new fluctuations at a faster rate than the stochastic decay (-1), thus yielding a net growth rate of $\eta_a \Delta' (R-1) / X_d$. The electric field profile results from a helicity conserving Ohm's law that is of the Fokker-Planck type.

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MONTE CARLO SIMULATIONS OF PARTICLE TRANSPORT IN STELLARATORS

by

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ABSTRACT

A rapid computer simulation has been developed which is an extension of our previous work with a purely bounce-averaged formalism. Particles ripple trapped in the local magnetic wells of the stellarator field are followed by iteratively conserving their action, J . Particles in an appropriately narrow region on either side of the trap/detrap boundary are followed using guiding center equations of motion. The remaining particles have significant parallel velocity and are assumed to stream along field lines. To restrict the use of guiding center equations to as small a region of phase space as possible, it is necessary to introduce an "effective" well formulation for the stellarator field, analogous to that often used for rippled tokamaks.

Also discussed is a modification to analytic theory of particle transport due to entrapping/detrapping in local magnetic wells in the presence of a radial electric field. This modification effects the regime of collisionality that would be typical of ions in a reactor. It predicts values of the diffusion coefficient that are lower than previous estimates and independent of collision frequency in the range of applicability. Numerical results of a bounce-averaged Monte Carlo simulation which confirm this scaling are presented.

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RF STABILIZATION OF INTERCHANGE MODES IN
MIRROR PLASMAS BY RESONANT SIDEBAND COUPLING*

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We have shown previously¹ that nonresonant ICRF sideband coupling can stabilize flute-interchange modes if $\omega_0 < \omega_{ci}$ (ω_0 is the frequency of the applied RF power and ω_{ci} is the local ion cyclotron frequency). In this paper we demonstrate that interchange modes can also be RF stabilized for $\omega_0 > \omega_{ci}$ by resonant² sideband coupling. Stabilization is possible for ω_0 near ω_{ci} and harmonics of ω_{ci} due to resonant coupling with either ion cyclotron or ion Bernstein sidebands, and also for ω_0 near the lower-hybrid frequency due to coupling with lower-hybrid resonant sidebands. Stability conditions will be presented in terms of the required RF electric fields.

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

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FEEDBACK CONTROL OF MAGNETIC ISLANDS IN TOKAMAKS^{*}

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The successful control of magnetic island development in tokamaks could have definite advantages. Elimination of sawtoothing might allow operation with higher currents and more peaked current profiles, with q on axis well below unity. Control of the $m = 2$ mode could help avoid plasma disruption. Deliberate steepening of the q - profile at $q = 2$, using feedback to suppress the $m = 2$ mode, could be used to stabilize neighboring modes.¹ The simulation of feedback stabilization for $m \geq 2$ has already been carried out.² The stabilizing effect of localized heating and current drive are easily obtained from the nonlinear magnetic island development.^{3,4} We have also carried out simulations of stabilization of the sawtooth ($m = 1$) mode. Control of this mode at high temperatures is somewhat problematical, because of the singular nonlinear development arising from its proximity to ideal instability. However, control of this mode in an indented configuration,⁵ where the ideal mode is stable, is more promising, and is currently under investigation. Stabilization of the $m = 1$ mode for $q(0) < 1$ could help stabilize all other kink modes.⁶

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

THEORY OF ENERGETIC TRAPPED PARTICLE-INDUCED RESISTIVE BALLOONING MODES*

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In recent electron cyclotron resonance heating (ECRH) studies¹, the achievable beta value has been observed to saturate at a level lower than what would have been predicted by ideal ballooning mode theory, and the resulting decrease in confinement is accompanied by enhanced magnetic fluctuations with $m \geq 3$. Since these experiments also suggest the existence of a significant population of trapped energetic particles, we have been motivated to investigate the influence of the latter on resistive ballooning modes as a possible theoretical explanation. In our work, a maximal ordering scheme is adopted which allows hot particle effects to be treated on the same footing as the core plasma. Corresponding flux-surface-averaged eigenmode equations as well as stability properties will be presented.

¹ Robinson, D.C., et. al., Proc. Tenth International Conf. on Plasma Physics and Controlled Nuclear Fusion Research (1984), to be published.

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Abstract submitted to the 1985 Sherwood Theory Conference, April 15-17, 1985, University of Wisconsin, Madison, Wisconsin.

Numerical Simulations of "Turbulent Trapping" and the Bump-on-Tail Instability. K. Theilhaber, Electronics Research Laboratory, University of California, Berkeley, CA 94720; D. Pesme and G. Laval, Centre de Physique Théorique, Ecole Polytechnique, 91128 Palaiseau, France.

Theoretical studies (1) strongly suggest that in the presence of sufficient turbulence, the growth rate of the weak warm-beam instability is significantly modified from its quasilinear value, and that a concurrent modification of velocity-space diffusion should occur. The criterion is approximately $(k^2 D)^{1/3} > \gamma$, where D is the quasilinear diffusion coefficient, and γ the quasilinear growth rate. This is in fact a regime always attained after a sufficient number of e-foldings. We numerically study the old paradigm of quasilinear theory by starting the instability in the presence of an initial turbulence, for a one-species, one-dimensional configuration. We shall present results for growth-rates, diffusion, and the correlation functions of the distribution function. In particular, we shall show the links to the "clump" turbulence of T.H. Dupree and co-workers (2).

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EQUILIBRIUM AND STABILITY OF HIGHLY ELONGATED TOKAMAKS

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Highly elongated tokamaks may achieve ohmic ignition with moderate toroidal fields and compact sizes.¹ To investigate this possibility, free boundary equilibria have been made for elongation, E , varying from 4 to 11. The attainable elongation is sensitive to the flatness of the current profile. Equilibria with peaked current profiles have been made for $E < 7$. With proper shaping of the plasma surface, the plasmas have a single elliptic magnetic axis. However, when the sides of the equilibrium cross section are held straight, up to five internal magnetic axes are formed for $E > 7$. The shape of the plasma surface also controls the elongation of the interior flux surfaces. For flat current profiles, the elongation profile in turn controls the safety factor profile, q . Since the elongation profile tends to peak on the magnetic axis, non-monotonic q profiles are made. The radial location of the minimum of the q profile may be varied by changing the flatness of the current profile.

The ideal MHD stability is closely tied to the radial location of the minimum in the q profile. If the minimum is near the plasma surface and the ends are triangularly shaped, equilibria can be made stable to ballooning modes for $\beta \sim 12\%$. When the minimum is shifted toward the magnetic axis, increasing the shear near the plasma surface, external kink modes can be wall stabilized with the wall located at three tenths of the minor radius.

Additional stability results will be presented for internal kink stability and stability to resistive axisymmetric modes.

¹R.W. Harvey *et al.*, *Ohmic Ignition of an Elongated Tokamak*, this meeting.

SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

Spectrum of Ion-Temperature Gradient Driven
Turbulence and Particle Transport in Tokamaks**G.S. Lee and P.H. Diamond*

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The results of analytical investigations of ion-temperature gradient driven turbulence are discussed in the context of modeling particle transport in tokamaks. η_i -modes are electrostatic ion-drift instabilities which result from coupling of ion-pressure fluctuations, driven by convective relaxation of the average ion-temperature gradient, to sound waves. Previously, we identified a saturation mechanism and corresponding spatial (mixing-length) and temporal scales (eddy turnover time) for saturated ion-temperature gradient driven turbulence using a mixing-length theory.¹ Results indicate that turbulent mixing of pressure fluctuations over the nonlinear radial mixing-length, Δ^c , and convective transport of parallel ion velocity, $\tilde{v}_{\parallel}$, affect coupling to sound wave by interaction with effective parallel ion viscosity ($\sim \mu_{\parallel} k_{\parallel}^2$) via turbulent radial diffusion. As an extension of this investigation, the two-point (energy-spectrum) equation is solved for several Reynolds number regimes and the wavenumber spectrum and the level of potential fluctuations $(e\Phi/T_e)_{rms}$ are calculated. With these results, we predict Ion-Mixing driven quasi-linear inward particle flux², particle confinement properties of Pellet-fueled tokamaks³ and energy confinement in beam-heated 'density clamped' (flat density gradient operation) tokamaks.

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SHERWOOD THEORY MEETING 1985
 Madison, Wisconsin
 April 15 to 17

**Particle Simulation of the Ion Mixing Mode
 in a Sheared Magnetic Field***

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Recent pellet-fueled tokamak experiments¹ have stimulated interest in ion temperature gradient-driven instabilities in order to explain rapid ($\sim 100\mu\text{sec}$) temperature and density profile relaxation. The ion mixing mode² is unstable for a certain threshold, η_c , in a sheared magnetic field and tends to mix hot and cold ion populations as the instability develops. The effects of finite electron-ion collisionality produces a net inward particle flux.

In order to investigate the nonlinear evolution and saturation of the ion mixing mode we have performed two and three dimensional particle simulations using a full dynamic ions, guiding center electron model. The simulations are carried out in slab geometry with strongly sheared magnetic field. A Monte-Carlo collision operator which simulates small angle collisions is used to incorporate electron-ion collisionality correctly. Gradients in the ion and electron temperature and density profiles are imposed initially.

The simulation results indicate the presence of unstable ion mixing modes with linear growth rates and real frequencies in agreement with the linear theory in sheared slab geometry. Quasilinear relaxation of the ion temperature profile appears to be the dominant saturation mechanism³ for the single rational surface case. There is evidence of parallel ion heating and mode coupling when a larger range of $k_y\rho_s$ is chosen. Test particle orbits are used to determine the resultant particle flux. The results are compared with the three dimensional case where multiple rational surfaces are present and the $(k_y - k_z)$ eigenmode interaction dominates. Comparisons with quasilinear and a fully nonlinear⁴ theory are also made.

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**Linear Modes and Nonlinear Vortex States
in Inhomogeneous Rotating Plasmas**

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We consider low frequency electrostatic drift modes and their corresponding dipolar vortex states derived from the nonlinear equations containing the $E \times B$ convective derivative. For both the drift wave¹ $k_{\parallel} v_e > \omega$ and the flute $k_{\parallel} v_e < \omega$ modes we show that the dispersion relations for the dipolar vortices and linear modes are complementary in covering all propagations (phase) speeds c . The drift wave vortex propagation bands are unbounded on either side $c > v_{de}$ and $c < 0$ of the bounded linear mode spectrum $0 < c = \omega/k_y < v_{de}$. Flute modes in a rotating plasma have two bands of vortex propagation separated by two bands of linear modes (one unstable and one stable band for MHD unstable systems). Monopolar and dipolar vortex states have been observed in rotating shallow water experiments³ where the equations are similar. The experiments of Antonova *et al.* show coalescence of small vortices into a large dipolar vortex.

The energy required to excite the vortices vanishes for parameters where their speed approaches that of the linear modes. The maximum potential ϕ_m in the core of the vortex scales with exterior scale size $1/k_{\perp}$ according to the mixing length rule $e\phi_m/T \simeq 1/2k_{\perp}r_n$.

Initially axisymmetric regions of vorticity in a uniform background are not steady state solutions. They deform, radiate and translate. We will discuss the interrelationship of these effects and their possible relevance to transport.

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BETATRON MODIFIED ION-ACOUSTIC INSTABILITY OF THE
BENNETT EQUILIBRIUM

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ABSTRACT

A new low frequency electrostatic instability is found for the Bennett equilibrium. The instability is of the ion-acoustic type and is primarily driven by the equilibrium electron drift. For large wavelengths the ion betatron motion has a stabilising influence and causes a significant shift in the real frequency. A simplified dispersion relation is obtained from a general nonlocal kinetic stability analysis. The dispersion relation is examined for electrostatic as well as electromagnetic instabilities. Both numerical and analytic results are presented.

SURVEY OF H-MODE EXPERIMENTS AND COMPARISON WITH THEORY

F. WAGNER

H. mod. // F. Pinker's theory!

IDEAL MHD BETA-LIMITS AND SCALING LAWS*

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Ideal MHD instabilities are expected to set a limit on the achievable beta in Tokamaks. In particular there are two instabilities which are considered the most limiting. These are the free-boundary external kink mode, with a toroidal mode-number of unity, and the large-n ballooning mode. In general the external kink mode is considered the more limiting of the two, however it is also susceptible to stabilization by modifying the external boundary conditions. In which case the ballooning mode is the limiting instability, and current profiles arranged to be marginal to this mode determine the maximum achievable beta. Several numerical studies have attempted to determine the beta limit as a function of the, numerous, plasma parameters, in particular relating to the geometry and current profile. These studies have attempted to combine their results in scaling laws, several of which exist, all obtained numerically and have been applied in various contexts. The one law¹ which has attracted a lot of attention relates the beta limit to the total plasma current, the minor radius and the toroidal field, $\beta_{\max} = c \mu_0 I/aB$, where c is a constant with a value of 2.2 when defining the kink-limit. It is relatively easy to show that the other scaling laws can be reduced to this form with differing values for the constant c , ranging from the 2.2 up to 3.5. This form of scaling law combines the virtue of simplicity with an easily tested relevance to experiment. This is largely responsible for its success, especially with the experimentalists. However it remains an empirical scaling law, based on numerical results and yields scanty insight to the physics underlying it. We propose a new form of scaling law relating to the maximum achievable beta-poloidal, rather than beta, and introduce the importance of the magnetic shear. We will also address the relationship with the simpler I/aB scaling law, as well as indicate new experimental avenues that are created.

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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

Explosive Coalescence of Magnetic Islands**T. Tajima and J.-I. Sakai^(a)*

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An explosive reconnection process associated with the nonlinear evolution of the coalescence instability is found through studies of the electromagnetic particle simulation and the magnetohydrodynamic particle simulation. The explosive coalescence is a process of magnetic collapse, in which we find the magnetic and electrostatic field energies and temperatures (ion temperature in the coalescing direction, in particular) explode toward the explosion time t_o as $(t_o - t)^{-8/3}$, $(t_o - t)^{-4}$ and $(t_o - t)^{-8/3}$, respectively for a canonical case. Single-peak, double-peak, and triple-peak structures of magnetic, temperature, and electrostatic energy, respectively, are observed on the simulation as overshoot amplitude oscillations and are theoretically explained. The heuristic model of Brunel and Tajima is extended to this explosive coalescence to extract the basic process. Since the explosive coalescence exhibit self-similarity, a temporal universality, we theoretically search for a self-similar solution to the two-fluid plasma equations. Our theory produces the indices of explosion in agreement with our simulation results. A simplified version of the governing equation for the scale factor takes a form of the orbital equation in the Sagdeev potential, where the potential energy assumes a form of gravitational potential and the centrifugal energy. For the coalescence to go explosive, the "total energy" ϵ has to be close to zero and the explosion time is given as $\sqrt{2}a_o^{3/2}t_a/3$, where a_o is the scale factor at $t = 0$ and t_A the Alfvén time. Explosive acceleration of particles m_o binormal to the magnetic field B_y and electrostatic field E_x becomes possible during the magnetic collapse and yields the maximum momentum $p_z^{max} \simeq m_o c(E_x/B_y)/[1 - (E_x/B_y)^2]^{1/2}$, because E_x^2 diverges faster than B_y^2 . Applications to spheromac formation, ring coalescence, doublet stability, and the half-coalescence of tokamak $m = 1$ mode are discussed.

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SUBCRITICAL MHD TURBULENCE*

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Numerical simulations of a simple two-dimensional model for MHD ballooning modes have shown stationary states of turbulence with large transport well below the critical beta for linear instability at long wavelengths. The phenomenon is thought to be similar to the well known subcritical turbulence in plane-parallel pipe flow. In the MHD model for a tokamak, each mode labeled by its cross-field wave number $\vec{k}_\perp$ balloons to the bad curvature region. The modes have an effective parallel wave number $k_\parallel$ corresponding to an inverse connection length Rq and curvature drift $g = L_p/R$ times the diamagnetic drift. L_p^{-1} is the inverse equilibrium pressure gradient length. The model consists of normalized equations for vorticity, Ohm's law, and convection to advance the perturbations in electric potential $\tilde{\phi}_k$, vector potential $\tilde{A}_k$, and pressure $\tilde{P}_k$:

$$\begin{aligned}\frac{\tilde{d}}{dt} k_\perp^2 \tilde{\phi}_k &= ig\omega_* \tilde{P}_k - \tilde{\nabla}_\parallel (k_\perp^2 \tilde{A}_k) - \gamma_k^\phi k_\perp^2 \tilde{\phi}_k, \\ \frac{\partial}{\partial t} \tilde{A}_k &= -\frac{\tilde{\nabla}_\parallel}{\beta} \tilde{\phi}_k - \gamma_k^A \tilde{A}_k, \\ \frac{\tilde{d}}{dt} \tilde{P}_k &= -i\omega_* \tilde{\phi}_k - \gamma_k^P \tilde{P}_k.\end{aligned}$$

The nonlinear mode couplings are contained in the $\tilde{E} \times B_0$ convective time derivatives ($\tilde{d}/dt = \partial/\partial t + \tilde{v}_E \cdot \nabla_\perp$) and magnetic flutter ($\tilde{\nabla}_\parallel = ik_\parallel + \tilde{B}_\perp/B_0 \cdot \nabla_\perp$). The dissipation rates ($\gamma_k^\phi, \gamma_k^A, \gamma_k^P$) are contrived to be equal ($= \gamma_k^d$) so as not to excite extraneous short wave dissipative instabilities. This leaves only the ideal instability at $\beta > \beta_{\text{crit}} = k_\parallel^2/g \equiv (L_p/R)/q^2$. When the spectrum for γ_k^d allows some marginally damped modes at intermediate $k_\perp$, transport persists at all β . When these modes are damped as all others, transport persists above $\beta \gtrsim \frac{1}{2}\beta_{\text{crit}}$. In the marginally damped case, the phenomenon is explained by demonstrated linear instability about secondary equilibria consisting of a zero frequency linear wave superposed on the primary equilibrium. Some aspects of the many wave (31×31) simulation persist in the triplet representation of the system.

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Energy Confinement Time due to Ballooning Modes in the Large Power Limit

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Using the ballooning model transport model suggested by Conner et al.^[1] we have investigated the energy confinement in a tokamak heated by a large amount of auxiliary power, $P_{aux} \gg P_{ohm}$. Our calculation differs from theirs in two significant ways: (1) we assume that the auxiliary power is sufficiently large that virtually the entire profile is unstable to ballooning modes and (2) we introduce a more realistic model to account for sawtooth oscillations near the center of the discharge. Our results show that for a given ballooning mode stability boundary, $\alpha = f(s)$, there is a unique energy confinement time. No free parameters exist, nor is confinement measured in terms of degradation with respect to some ohmic scaling law. The form of the energy confinement time is found to be

$$\tau_E = \frac{a^3 B_\phi^2}{P_{aux}} g(q_a)$$

The function g depends only on q_a and the functional dependence of $f(s)$. The $1/P_{aux}$ dependence is a consequence of the fact that the pressure profile is independent of P_{aux} when transport is dominated by ballooning modes [i.e. $p(r)$ depends only on $f(s)$] and the definition of τ_E [i.e. $\tau_E \equiv \int 3nT d^3r / P_{aux}$]. We suggest that the $1/P_{aux}$ scaling result should be considered as generically true. For all very strongly heated plasmas operating along the marginally stability boundary for ballooning modes, the corresponding energy confinement time must scale as $\tau_E \sim 1/P_{aux}$.

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NEOCLASSICAL MHD INSTABILITIES AND TRANSPORT IN TOKAMAKS

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The moment equation approach to neoclassical-type processes is used to derive [1] the perturbed flows, currents and resistive MHD-like equations for studying instabilities in tokamak plasmas. These "neoclassical MHD" equations are valid for arbitrary collisionality ν_* and low to medium mode number modes for which the electrons are fluidlike. The main differences from the regular resistive MHD equations are: (1) the effective polarization current has ρ_m/B^2 replaced by ρ_m/B_θ^2 , where B_θ is the poloidal magnetic field; (2) Pfirsch-Schlüter currents cancel the geodesic curvature terms; (3) the flux-surface-averaged Ohm's law contains a (fluctuating) bootstrap current contribution due to the parallel viscous damping (at rate $\mu_e \sim \sqrt{\epsilon} \nu_e / (1 + \nu_{*e})$) of pressure gradient driven poloidal flows. Possible "neoclassical MHD" instabilities include pressure-gradient-driven [1,2], tearing [3] and rippling type modes. The pressure gradient driven modes have growth rates $\gamma_\mu \approx n^{2/3} S_\theta^{1/3} \beta_\theta^{2/3} \times (\mu_e/\nu_e)^{1/3} / \tau_{A\theta} = [4(m_e/m_i) \mu_e \omega_{*e}^2]^{1/3}$ in an $\underline{E} \times \underline{B}$ toroidal rest frame ($\omega = \omega_E + i\gamma_\mu$) and radial extent $\delta_\mu \sim n^{-1/3} S_\theta^{-1/3} [\beta_\theta (\mu_e/\nu_e)^2]^{1/6}$. For $\gamma_\mu < \omega_{*e}$, diamagnetic drift frequency effects reduce the growth rate and radial extent by factors of $(\gamma_\mu/\omega_{*e})^2$ and $(\gamma_\mu/\omega_{*e})^{1/2}$, respectively.

To estimate the anomalous transport induced by the pressure-gradient-driven modes, we follow the procedures developed by Carreras and Diamond [4,5] for resistive ballooning instabilities. We find for the anomalous electron heat diffusivity $\chi_e \sim n_M^{1/2} (\eta/\mu_0) (\mu_e \beta_\theta / \nu_e)^2 \sqrt{m_i/m_e} / (1 + n_M^{2/3} \omega_{*o}^2 / \gamma_{\mu o}^2)^{3/4}$ where n_M is a maximum mode number for which the electrons are fluidlike. In the outer confinement region the ω_{*e} correction becomes negligible and $\mu_e/\nu_e \sim \sqrt{\epsilon}/\nu_{*e}$. Then, utilizing an ohmic power balance to determine the scaling of T_e , we find $\beta_\theta \sim (m_e/m_i)^{1/6} \sim 0.3$ and $\tau_E \sim n_e^{13/14} a^{4/7} R_0^{15/7} q^{5/7} B_p^{1/7}$, which is close to the TFTR empirical scaling law $\tau_E \sim n_e a R_0^2 q^{0.8}$. For $\nu_* < 1$ the estimated χ_e is similar to but slightly (by $1/\sqrt{\epsilon}$) larger than the Carreras-Diamond result [4,5]. We will also discuss the anomalous particle transport, toroidal momentum damping and possible modifications of the neoclassical pinch and bootstrap current effects due to neoclassical MHD turbulence in tokamak plasmas.

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*Research supported by the OFE/DOE under contract DE-AC02-80ER53104 (UW) and DE-AC05-84OR21400 (ORNL).

NONLINEAR WAVE-PARTICLE INTERACTIONS AT CYCLOTRON HARMONICS
WITH COLLISIONAL DECORRELATION*

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When particle orbits become trapped very near a cyclotron resonance, the quasilinear model of weakly perturbed, uncorrelated passages through resonance breaks down¹ and nonlinear effects become important if the wave-particle autocorrelation time is less than the collisional decorrelation time. Analytic formulae are derived describing the nonlinear behavior including relativistic detuning and perturbed bounce motion. The results include large energy excursions at bounce resonant values of the turning point,² and the connection to quasilinear behavior is made. It is also demonstrated that perpendicularly propagating waves at the second harmonic electron cyclotron harmonic frequency can strongly interact with very cold (< 1 eV) electrons.

Coulomb collisional decorrelation has been modeled for electrons trapped near the second harmonic resonance using a Monte Carlo code. Significant enhancement in the heating over the quasilinear model is found for certain ranges of collisionality and autocorrelation time.

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy under contract DE-AC02-80ER53104 with the University of Wisconsin and U.S. DOE Under contract DE-AC05-84OR21400 with Oak Ridge National Laboratory.

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A NEW SHORT WAVELENGTH MODE

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Motivated by the experimental observation in tokamaks that the electron energy transport is anomalous and larger than the particle transport, we have identified an unstable mode in the region between the ion and electron gyroradii driven by electron temperature gradient. Since the ion response in the regimes is adiabatic, the particle transport associated with the mode is indeed absent. The finite β effects of this mode shows that the electrostatic unstable mode leads to magnetic perturbations on the typical scale length of the collisionless skin depth. Detailed numerical studies of two coupled integral equations for ϕ and A and parametric studies will be presented. The implication of this new mode to energy transport in tokamaks will be discussed.

*Work supported by DOE.

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EFFECT OF ELECTRON TAIL ON ION BERNSTEIN MODES

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The effect of current drive on ICRF heating by ion Bernstein waves (IBW) is studied in the limit of low β_i ($< m_e/M_i$) and also high β_i ($> m_e/M_i$). The parallel electron distribution function is modelled by a background Maxwellian with a long flat tail, in accord with both experimental observations and theoretical predictions. The principal effects found are: a) for the initial value problem (fixed k) a stable tail mode appears which can, in some parameter regimes, couple to the IBW causing a detuning near the second harmonic of the cyclotron frequency; b) for the boundary value problem (fixed $k_{\parallel}$, ω) there is enhanced spatial damping due to resonance with tail electrons. To facilitate an understanding of mode conversion near the second harmonic, we also analyze in detail the small $k_{\perp}\rho_i$ limit. The presence of the tail modifies the electron dielectric response, allowing the propagation of modes which would otherwise be evanescent. In the low β_i limit the IBW can couple with this new mode, and many reduce the amount of energy that reaches the second harmonic resonances. In the high β_i limit the simultaneous presence of the IBW, fast wave and the normally evanescent mode significantly changes the coupling topology. An important effect is the appearance of trapped waves in non-resonant regions, where the dissipation will be through electrons. This will modify the character of the mode conversion and hence the ion heating efficiency.

SIMULATION OF HIGH-BETA TOKAMAK START-UP

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The Columbia High-Beta Tokamak (HBT) is simulated in the start-up phase by our axisymmetric resistive MHD code. The code is an improvement of the previous codes used by Lui and by Izzo, in that the coil currents (and not the poloidal flux) are now prescribed as functions of time, and that a much larger vacuum region is included for self-consistency. Numerical instability, which typically arises with ADI schemes when the plasma region adjoins a vacuum region, is avoided by the use of a matrix tri-diagonal inversion scheme.

Equilibrium is attained after toroidal field reversal. The time-behavior of the plasma current showed some surprising features: for example, a rapid drop to equilibrium values immediately following reversal. This phenomenon, hitherto unnoticed, has been verified in actual experiments on the HBT.

This method is now being applied to study the formation of bean-shaped plasmas.

Work supported by USDOE.

Influence of Openings On Nuclear Characteristics of a Fusion Reactor Blanket

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ABSTRACT

In recent years, it has been shown that the nonhomogeneities caused by openings in blanket (for vacuum pumping, plasma heating, maintenance ports, etc.) dramatically depress the tritium breeding ratio, TBR, and other nuclear characteristics of a blanket.^{1,2}

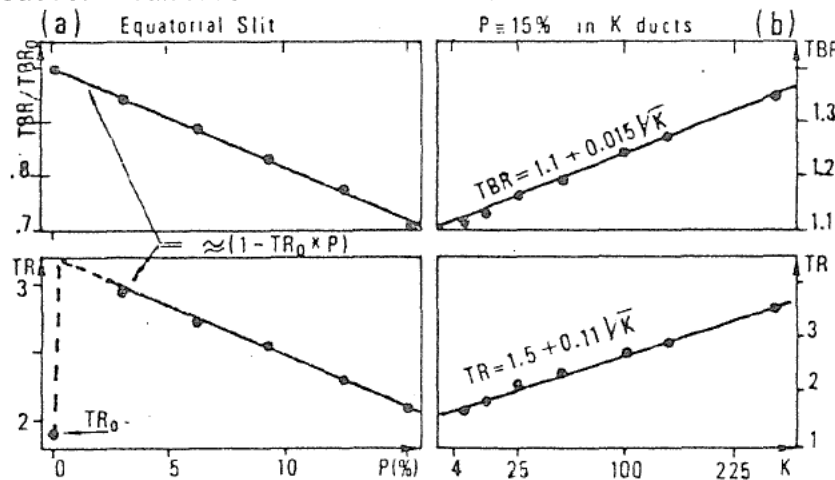
The object under study is the fusion reactor based on tokamak physics. The reference unit is that as proposed by ANL-Argonne³ version with 1.2 cm of first wall, 35 cm Li₂O Breeder, Water Cooling, PCA, Plenum and Shield. Additionally 6 cm of Be multiplier has been introduced after the first 2 cm of breeder.

Numerical tool used: 3DAMC-VINIA code - this is a 3-D analytical Monte Carlo treatment which has no numerical approximation, no limit as to the surface type and number to be inserted, and the full data library in ENDF/B format is used without any pretreatment.

The figure shows an example of our calculation (points). Part (a) of the figure presents relative changes of TBR and the number of neutron transitions through plasma chamber, TR, as a function of the equatorial slit opening in the breeder, P(in %); TR₀ is for no port case. Part (b) presents TBR and TR dependence on the port division into K tubes directed at the torus axis. The total opening area remains constant P=15%.

Analysis of the numerical results lead to the following observations: (i) it is possible to parametrize TBR, energy depositions, (ED), and neutron leakage from the blanket, (NL), by use of TR₀ (or breeder reflectivity). TR₀ is 1.5, 1.9, 2.4, 2.7 respectively for Li₂O, Li₂O(Be), LiAlO₂(Be), ¹⁷Li⁸³Pb breeders. (ii) The TBR, ED, and TR increase as the port number increases (for constant P) as linear function of $\sqrt{K}$ (or equivalently internal surface of the port tubes); their radial distribution also changes with K.

The above observations point to the importance of reflectivity of the blanket region closest to the plasma, as well as the return flux of neutrons through the small openings on the magnitude of the nuclear characteristics of the fusion reactor blanket.



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 ORAL Session

Vacuum Ripple Fields for Improved MHD Stability *

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Recent work on low frequency MHD modes in long thin geometries has produced encouraging results:¹⁻³ a conducting wall in combination with finite- β effects can stabilize an axisymmetric mirror plasma; for quadrupole tandem-mirror systems, the plug β 's necessary for global stability have been reduced, and a new region of stability at high central-cell β has been introduced.

While pressure anisotropy aids stability ($\beta_{crit} \rightarrow (R - 1) * L_p^2 / L_{vac}^2$ in low β with a near wall), at typical plug mirror ratios β may be unacceptably large, for both axisymmetric and high central-cell- β quadrupole systems. An isotropic pressure, however, is stable for $\beta > .5$ in the near wall, low mirror ratio limit. To exploit this result, we add a low amplitude ripple to the central-cell vacuum magnetic field. This increases the contribution of the long, low mirror ratio, isotropic portion of the machine to the axial stability integral. Results are presented showing how much ripple is necessary to achieve $\beta_{crit} = .5$, as well as how the improved system fares at finite wall distances.

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Resonance absorption vs rf stabilization*

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Numerical solutions of the cold plasma equations show that for $\omega_A(0) < \omega < \omega_{ci}$ an externally driven wave is resonantly absorbed in a thin layer within the density gradient where $\omega_A(x) = \omega$, where $\omega_A(x)$ is the local value of the shear Alfvén frequency, $\omega_A^2/\omega_{ci}^2 = k_z^2 V_A^2/(\omega_{ci}^2 + k_z^2 V_A^2)$. Note that this is close to the outer edge if ω is close to ω_{ci} . In general the wave structure will be affected by this absorption even at spatial locations not near the resonance. For some antenna configurations the wave strongly peaks in amplitude at the spatial location of the resonance and has a strongly reduced amplitude in the interior. In contrast for $\omega > \omega_{ci}$ no Alfvén resonance is possible and the wave has an evanescent character with sizeable amplitude throughout the plasma. This result is offered as a major contributing factor in the explanation of the sudden appearance in Phaedrus¹ of rf stabilization when the driving frequency is changed from just below ω_{ci} to just above ω_{ci} . This result does not deny the relevance of nonlinear dynamics for the stabilization, but rather shows that linear wave propagation characteristics may have enough complexity to explain a major feature of the experiment. In addition it includes the standard cold plasma result for ω near ω_{ci} , that the wave in the plasma is almost entirely right hand polarized, i.e., there is no significant *particle* resonance at $\omega = \omega_{ci}$ in the linear regime. There are global *mode* resonances near ω_{ci} that play a role in enhancing the plasma field for a given antenna signal. The relevance of this cold plasma result to a warm plasma is still to be determined.

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

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A MODEL OF THE PLASMA-SHEATH REGION INCLUDING*
SECONDARY ELECTRON EMISSION AND ION REFLECTION

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A low temperature plasma interacts with a collector plate primarily through the emission of secondary electrons and the reflection of plasma ions. These phenomena affect the electrostatic potential drop across the sheath region and hence plasma transport to the plate. The computer code PDW1 models this behavior. The code is a one-dimensional, time-dependent electrostatic particle simulation. Particle ions and electrons, with a reduced mass ratio, are injected continuously from a plasma region into a plate where ions are reflected or cold electrons are emitted. A parametric study of the dependence of potential drop on interaction coefficient and mass ratio is presented. We have also developed theory for the effect on potential of ion reflection, for the cases of $T_i=0$ and $T_i=T_e$, and of secondary electron emission for $T_i=T_e$. The simulation results for ion reflection approach those of our theory for the cold ion case. The simulation results with secondary electrons compare well with previous theory¹ for cold ions and demonstrate charge saturation as predicted.

¹G.D.Hobbs and J.A.Wesson, Plasma Physics, Vol.9, 86 (1967)

*Work supported by U.S.Department of Energy under contract DE-AT03-76ET53064.
Computation facilities provided by NMFECC.

Reversed Field Pinch Calculations Using A Reduced Set of Equations*

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The study of the turbulent dynamo effect¹ in the reversed field pinch configuration using the resistive MHD model involves the excitation and interaction of a large number of plasma modes. Assuming a full set of MHD equations and realistic parameters for present RFP devices, it is found that numerical calculations exceed the available resources of the present computers both in terms of storage and time requirements. In order to facilitate the study of resistive MHD turbulence in the RFP configuration, we have adopted a reduced set of equations due to Strauss,² which are derived in the limits of low β , force free plasmas with the dynamical fluctuations ordered to be small and a slow time scale ordering which eliminates the fast compressional Alfvén waves. These equations require the time advancement of only two dynamical quantities, a magnetic flux function and a vorticity component. This reduction leads to increased computer speed and decreased storage compared with the full equations.

Computational results using these equations are compared with those of previous calculations, both for the RFP and tokamak configurations, using a full set of MHD equations. In particular, we observe the nonlinear mode stabilization mechanism due to the dynamical couplings which was reported previously.³ In addition, we present some initial results in the use of these equations to study resistive MHD turbulence.

* 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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FAST WAVE HEATING IN TOKAMAK AND STELLARATOR MAGNETIC FIELDS*

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ABSTRACT

It has been suggested that fast wave plasma heating at the fundamental cyclotron frequency of the bulk ions may be enhanced in stellarator geometry.^{1,2} We intend to address this question by solving Maxwell's equations for the ICRF wave fields in a helically symmetric stellarator magnetic field. Preliminary calculations for a straight tokamak with and without poloidal magnetic fields show no resonant heating at the fundamental cyclotron resonance. However, heating at the two ion hybrid resonance is observed. Energy deposition profiles and antenna loading impedance are calculated in the two ion hybrid case.

*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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**LOWER HYBRID CURRENT RAMPING
IN THE PRESENCE OF RUNAWAY ELECTRONS
AND NONLINEAR WAVE INSTABILITIES***

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In lower hybrid current ramping experiments, the plasma current depends crucially on the inductive field and the lower hybrid wave spectrum. At large inductive fields, the dependences can be quite involved because of the contribution of runaway electrons. This is further complicated by the possibility that "runaway" distributions can be unstable to anomalous Doppler instabilities. These instabilities can clamp runaway electrons via wave pitch-angle scattering and change lower hybrid current ramping both qualitatively and quantitatively. A Fokker-Planck quasilinear code is used to study modifications in this nonlinear regime. We show that a redistribution of current carriers will have a significant impact on current ramping efficiency.

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HELICALLY SYMMETRIC RESISTIVE EQUILIBRIA FOR RFP*

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A self-consistent procedure based on the resistive MHD equations is formulated for finding equilibria in a helically symmetric geometry. It has previously been shown that solutions to this system may exhibit a reversal of q-profile, a characteristic feature of RFP's, via the translational transform of the helically symmetric fields¹. Furthermore, recent computer simulations have indicated that steady state solutions to such systems exist².

In the present work, the resistive MHD equations are reduced to a set of scalar equations in terms of the stream functions introduced for various divergence-free vectors. The resulting set is analyzed for both analytic tractability and physical applicability. Various dynamo models which have been proposed earlier can be identified as special cases of the general system considered in proper limits. One special case that we consider has the mass flow aligned with the line of symmetry. In this case, magnetic surfaces, given by $\psi = \text{const.}$, are governed by a second order partial differential equation with one free function of ψ . Explicit expressions for other physical quantities have also been obtained in terms of ψ . If one then further assumes that the unidirectional flow along the symmetry lines is small, nonlinear flow terms can be neglected and a force free state with a specific form of the above mentioned free function of ψ appears. In this limiting form of flow, difficulties associated with incorporating the Ohm's law within the force free equilibrium model may be resolved. Specifically, this result suggests that the force free RFP models previously considered³ may be reconciled with the Ohm's law in the presence of small unidirectional flow and for the specific choice of aforementioned free function. Solutions to the finite unidirectional flow case and the case of small unidirectional flow with the consequence of a force-free state are investigated for possible applications to RFP.

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NEOCLASSICAL TRANSPORT IN TOKAMAKS WITH DIVERTORS*

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The effect of a separatrix on ion neoclassical transport is investigated. The ion temperature at the plasma edge is determined by a balance between radial energy flow from the plasma interior and parallel flow to the divertor chamber. In the high collisionality regime, a bifurcation may occur, corresponding to the L - to H -mode transition in the ASDEX tokamak. In the low collisionality regime, the ion temperature gradient is large and the plasma edge is thermally stable. The ion energy confinement time then scales linearly with plasma current and is very sensitive to improvements in particle confinement.

*Supported by U.S. Department of Energy Contract No. DE-AT03-84ER53158.

The Establishment of the Electrostatic Field
In a Stellarator

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ABSTRACT

In order to simulate the development of an ambipolar electrostatic field in a stellarator, a particle-in-cell calculation has been performed. The code uses a rectangular grid, one axis of which corresponds to the poloidal angle and the other to the minor radius.¹ In the former direction periodic boundary conditions are applied, in the latter a reflecting boundary is used on the 'inside' and an absorbing boundary on the 'outside'. Toroidal angle corresponds to the third Cartesian coordinate. A vacuum stellarator field was used in the simulation, which shows the evolution of the surfaces of the electrostatic potential. In general the potential surfaces do not coincide very closely with the magnetic surfaces in an $\ell=3$ stellarator.

This work was supported by U.S. Department of Energy Contract No. DE-AC02-84ER53166 and the National Science Foundation Grant No. ECS-8206027.

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Correlation Function and
Spectral Density Distribution
for the Stochastic Motion*

L. Bromberg and A.B. Rechester

Fourier transform $a(\omega_n)$, $\omega_n = 2\pi n/T$ of the dynamical motion which is stochastic (has a positive Liapunov number) is a very sensitive function of initial conditions and does not converge in the limit $T \rightarrow \infty$. Thus physical quantities like correlation function etc. can not be expressed directly through $a(\omega_n)$. We introduce time partition similar to space partition in statistical mechanics. This allows us to express unique physical quantities through statistical quantities $a(\omega_n)$. One point distribution function based on this partition is Gaussian $P(a_n) = 2|a_n| \exp\{-|a_n|^2/\Delta_n\}/\Delta_n$ with $\Delta_n = \langle |a_n|^2 \rangle$. Numerical computations are in excellent agreement with the theory.

* Work supported by U.S. Department of Energy Contract #DE-ACO2-78ET-510B.

NEARLY PERPENDICULAR WAVE PROPAGATION AT THE FUNDAMENTAL ELECTRON CYCLOTRON RESONANCE

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ABSTRACT

Waves propagating nearly perpendicular to the equilibrium magnetic field across the fundamental electron cyclotron resonance layer are studied by a boundary layer analysis analogous to that previously used in the second harmonic resonance.¹ The plasma is assumed to be perpendicularly stratified, and represented by the relativistic, linearized Vlasov equation. Field equations valid within the boundary layer are derived by calculating the current from the rescaled and reordered Vlasov equation. These equations lead to the well-known weakly relativistic dispersion relation for the fundamental resonance when the equilibrium field is uniform. The asymptotic solutions obtained for these equations connect to the results of the geometrical optics formalism of Weitzner and Batchelor.² It is shown that to the lowest significant order in the expansion parameter $\eta = v_e/c$, where v_e is the electron thermal speed, the wave energy associated with the ordinary mode transmitted through the resonance layer is independent of the relativistic corrections, for the case of nearly perpendicular propagation. It is also shown that there is no reflected energy associated with this mode when the waves are incident from the high-field side. These results generalize similar conclusions deduced by Antonsen and Manheimer³ in the nonrelativistic limit. Therefore, in the case of the high-field side incidence the geometrical optics is valid for the weakly relativistic case. Relativistic effects, however, are found to be important in the case of low-field side incidence when the parallel refractive index is small. It is shown that these effects produce a significant reduction in the reflection coefficient for this case from the nonrelativistic value given by Antonsen and Manheimer. Correspondingly, for this mode there is an increase by as much as a factor of two in the absorption rate for sufficiently high, but moderate, electron density and temperature. The effects associated with the non-geometrical optics domain are negligible as $n_{\parallel}$ becomes larger than η .

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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

**Stability Thresholds for Long Wavelength Precessional Modes
in Bumpy Torus Experiments***

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We analyze the "layer" precessional mode in an EBT configuration at arbitrary drift reversal. New effects are included by taking into account the Landau damping in perpendicular velocity space of the hot electrons. In particular, Landau damping arises from the inner edge of the hot electron profile, and inverse Landau damping from the outer edge. The inner edge Landau damping destabilizes the precessional mode. The problem is solved in a thin ring approximation for a cylindrical plasma with embedded currents. This simulates the role of field line curvature in the actual mirror experiment. It is found that the mode is destabilized when $\beta_h > \frac{1}{3}\kappa\Delta(\beta_h$ — the hot electron β -value, κ — the curvature, Δ — the thickness of hot electron ring) and that its growth rate is quite dependent on the coupling constant $\tilde{\omega}_\kappa/\gamma_{MHD}$ ($\tilde{\omega}_\kappa$ — the curvature drift frequency, γ_{MHD} — the MHD growth rate) and its axial structure. We conjecture that this mode is responsible for the T-M transition. It is possible that no experiment with hot electrons has achieved drift reversal in a simple mirror cell. The high beta observed experimentally can be achieved without drift reversal by having the energy stored over a substantially larger volume than is generally assumed. On the other hand, the growth rate can be quite small in certain parameter regimes, so that nonlinear saturation of the mode may be at a low enough level to allow drift reversal to be achieved. Further experimental measurements are needed.

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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

New Energy Source for Hot Particle Modes**H.V. Wong, H.L. Berk, and K. Tsang[†]*

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Hot particle modes differ from MHD modes in that the Lagrangian perturbed magnetic field is finite. This term can yield results that differ from MHD predictions, by stabilizing interchange modes, predicting fish-bone oscillations and producing negative energy precessional modes. Previous analyses tend to assume that the perturbed Lagrangian magnetic field is flute-like in character, which is true in the high bounce frequency limit for the hot particle modes. Here we point out that the deviation from the flute response in the low bounce frequency limit yields a new free energy source. This free energy source can destabilize magnetic compressional modes, as well as broaden the spectrum of precessional modes, which are destabilized when interacting with positive energy waves such as shear-Alfvén waves. The magnitude of this source is usually larger than the positive energy sources arising from the finite Larmor radius effects of the hot particles.

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

SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

**Numerical Investigation of Trapped Particles and
Ballooning Modes in Tokamaks***

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In order to study the behavior of energetic trapped particles in a tokamak, a code has been written to solve numerically the ballooning mode equation¹ with kinetic effects, including drift resonance. The feasibility of stabilization of ballooning modes by the energetic particles and "fishbone"-type instabilities² are areas of investigation that will be discussed.

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

**ENERGY CONFINEMENT TIME
OF TOKAMAK PLASMA WITH AUXILIARY HEATING**

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San Diego, California

The formulas for electron thermal diffusivity of tokamak plasmas with various heating methods are derived based on the phenomenological free energy argument. The experimental results appear to support the formula.

Ray Tracing of Fast Magnetosonic Waves in Tokamaks
Including Mode Conversion Effects*

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Princeton Plasma Physics Laboratory
Princeton University

A numerical code which combines a ray tracing analysis of the wave propagation¹ with a one-dimensional, fully kinetic analysis of the power deposition profiles² has been constructed to model recent fast magnetosonic wave heating experiments on PLT. Geometric focussing of the wave fields is modeled using ray tracing based on a warm multi-fluid dispersion relation in an axisymmetric tokamak equilibrium with circular, concentric flux surfaces. Previous treatments considered only rays reflected from the cyclotron absorption/mode conversion layer in the plasma core and hence could not accurately model experiments in which mode conversion to the ion Bernstein wave or transmission of power through the layer was significant. In our analysis, the relative proportion of incident power that is transmitted through, reflected from, mode converted at or absorbed in the layer is determined from kinetic one-dimensional full wave solutions for the fields obtained where the incident rays cross the layer. Transmitted rays are retained by including a small, heuristic collision frequency in the dispersion relation. The mode-converted wave is assumed to damp rapidly on the electrons and is not traced in the current model. Finally, the one-dimensional absorption profiles obtained from the kinetic analysis are mapped back onto the 2-d flux surfaces according to the ray paths. Results from the code for a range of experimental parameters will be presented.

*Work supported by DOE Contract No. DE-AC02-76-CHO-3073

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Theory of the Rippling Instability in Toroidal Devices

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The theory of the rippling instability has been developed for axisymmetric toroidal plasmas including ion viscosity and parallel electron heat conduction, but assuming that the growth rate is small compared to the wave angular frequency $\omega_0 = (1 + 1.71 \eta_e) \omega_e^*$ [ω_e^* is the electron diamagnetic velocity and $\eta_e \equiv (d \ln T_e / dr) / (d \ln N / dr)$]. Three instability regions must be considered, viz. $(c_i / R \omega_0)^2 < 0.12$ where cylindrical effects dominate and the plasma is stable; $0.12 < (c_i / R \omega_0)^2 < 0.26 q^2$ where the magnetic drift destabilizes the mode; and $0.26 q^2 < (c_i / R \omega_0)^2$ where the plasma is stable again (The numerical values are given for $\eta_e = \eta_i = 2$ and $T_e = T_i$). Parallel electron heat conduction is stabilizing but ion viscosity broadens the instability domain. Under certain conditions, an important top - bottom asymmetry of the density fluctuation spectrum may arise, suggesting perhaps an explanation to recent observations made in the TEXT Tokamak (K.W. Gentle et al., Plasma Physics and Controlled Fusion, 26, 1407, 1984).

NEUTRAL GAS MODELING IN STM AND TMX-U*

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The MCNT code⁽¹⁾, a full three-dimensional, time-independent, multi-species neutral gas transport code for general plasma and cavity geometries, has been applied to identify the dominant sources of neutral gas and the mechanisms of its transport in the TRW Symmetric Tandem Mirror (STM) and in TMX-Upgrade.

In the STM device, the dominant source of neutral gas is from wall recombination of the stream plasma on termination plates in the device end-cells, while the important sources of gas in TMX-U include energetic neutrals from beam injection, a cold molecular stream from the beamlines, gas box fueling, as well as gas released on limiters by wall recombination of edge plasma ions. Atomic and molecular density distributions have been calculated for these different gas sources and for several plasma operating conditions. Direct comparison shows good agreement with experimental data.

(1) B.I. Hauss and T.K. Samec, Bull. Am. Phys. Soc. 29, 1339 (1984).

* Work supported by US DOE DE-AC-03-79ET51017, TRW Subcontract to LLNL (#3441805) and TRW IR&D funds.

THE CYCLOTRON MASER INSTABILITY IN RELATIVISTIC PLASMAS:
WAVE GROWTH AND SATURATION*

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The electron-cyclotron maser instability involves the amplification of electromagnetic fluctuations near the electron cyclotron frequency Ω_e (or its harmonics) through a gyroresonant interaction driven by a population inversion in the electron velocity distribution. It has been recognized in both the laboratory¹ and space² plasma physics communities that inclusion of the relativistic mass dependence of the gyrofrequency is essential in describing the wave-particle interaction. Recent work³ has demonstrated that relativistic effects can also significantly modify wave dispersion near Ω_e when the characteristic electron energy satisfies $v^2/c^2 \gtrsim \omega_{pe}^2/\Omega_e^2 \ll 1$. In such relativistic plasmas the cyclotron maser instability leads to strong extraordinary-mode emission perpendicular to the magnetic field.

In the present paper, a systematic study of the growth and saturation of the maser instability is presented for the case of a Dory-Guest-Harris (loss-cone) distribution using linear and quasilinear theory and electromagnetic particle simulations. For $v_{lo}^2/c^2 > \omega_{pe}^2/\Omega_e^2$ the $k_{\parallel} = 0$ instability is confined to a narrow range with $kc/\Omega_e \lesssim 1$ and frequency just below Ω_e . A previous quasilinear analysis⁴ is extended to treat the case of strictly perpendicular emission. Although the linear growth rate decreases with decreasing values of ω_{pe}^2/Ω_e^2 , the saturation level is predicted to increase. This result is confirmed by the simulations. The maser instability is thus most efficient in a very low density plasma.

* Work supported by USDOE, NSF, and NASA.

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EQUILIBRIUM OF AXISYMMETRIC PLASMAS WITH FLOW

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The equilibrium of plasmas with flows is studied using the axisymmetric steady-state ideal MHD equations. An equation for the poloidal flux coupled with a Bernoulli law is derived. There are 4 prescribable flux functions, which are not completely arbitrary but have constraints between them. Numerical solutions with various types of flow in both the toroidal and poloidal directions will be shown.

A variational formulation of the problem will be presented that lends itself to investigating the bifurcation of the solutions. The influence of the different transitions on the bifurcations will be explored.

Work supported by USDOE.

MAGNETIC RECONNECTION OF A RESISTIVE DOUBLET
IN THE ADIABATIC LIMIT*

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ABSTRACT

Extremely fast iterative Back-Average algorithms have been used in an Alternating Dimension resistive code to measure the net reconnection flux, γ , of a doublet, excited by low frequency oscillations. Our results show conclusively that γ is positive in the adiabatic limit of zero resistivity and $\gamma = 0$ if and only if the modulation of the F-coil oscillations is zero.

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LARGE SAWTEETH AND MINOR DISRUPTIONS

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The stability of tokamak plasmas following a very large $q = 1$ sawtooth is investigated numerically using the equations of resistive MHD. The amplitude of the sawtooth is found to increase rapidly as the safety factor at the center is further decreased below one. Following a large sawtooth the originally peaked current profile is flattened across a broad plateau at the center beyond which the current drops precipitously. Because of the steepness of the resultant current gradient, even rather short wavelength modes are found to be unstable following the sawtooth. Typically, the fastest growing mode has a poloidal mode number m larger than two. The relationship between these results and experimental observations of both minor and multi-stage major disruptions is discussed.

Work supported by DOE

CONSTRUCTION OF A VARIATIONAL PRINCIPLE
FOR THE STEADY-STATE TWO-DIMENSIONAL
FOKKER-PLANCK EQUATION WITH STRONG RF DIFFUSION

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Numerical codes exist for calculating the distribution function described by the two-dimensional Fokker-Planck equation. A simple analytic form has also been given by V. B. Krapchev, D. W. Hewett and A. Bers^[1]. The aim of this work is to construct a variational principle for the current, giving an analytic expression in the limit of a large RF diffusion coefficient. The procedure involves constructing separate variational principles for the distribution function and the adjoint function (the solution of the adjoint equation)—this gives first order accurate trial functions that are used to obtain a second order accurate current. The problem is directly applicable to lower-hybrid current drive.

A B S T R A C T

**FOKKER-PLANK CALCULATIONS OF COULOMB COLLISIONAL EFFECTS
ON KINETIC REGIME WALL PLASMAS**

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One important parameter of the kinetic model wall plasma structures discussed in the accompanying paper by Neuman et. al. is ion heat flux from the main plasma. This parameter, unlike others of the system, depends on momentum transfer coulomb collisions. A Fokker-Plank code has been developed that conforms to the structure of the characteristic based kinetic model code. Calculations with this combined code show that the ion heat fluxes to be expected approach the classical flux limit. With this information the kinetic sheath solutions are uniquely determined.

A B S T R A C T

SENSITIVITY OF THE STRUCTURE OF KINETIC REGIME WALL PLASMAS
TO THEIR (MULTITUDE OF) PHYSICAL PARAMETERS

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Kinetic regime calculations* have previously shown plasma sheath structures with an electrostatic potential maximum, caused by ionization processes near a neutral gas emitting wall. These calculations have shown the existence of two parameter regimes, one in which stationary solutions exist and one in which they do not. In the regime where stationary solutions exist their characteristics, including plasma potential and ion heat flux, depend on, among other parameters,

- (1) fraction of wall incident plasma re-emitted as neutrals
- (2) division of emitted neutrals into reflected and thermal neutrals
- (3) magnitude of different electron impact and charge exchange ionization process
- (4) small but non-zero coulomb collision rates
- (5) secondary electron co-efficient of the wall
- (6) angle of B with respect to the wall
- (7) neutral pumping length

Studies will be shown of the sensitivity of solutions, in regimes of interest, to values of these parameters. One result of these calculations is the indication that the potential maximum, which has not yet been seen experimentally, should not be difficult to find.

*Gierszewski, P., McKenty, P., McCullen, J., and Morse, R.,
Structure of Wall Plasmas near Divertor Neutralizer Plates or Limiters,
Physical Review Letters, 49, 650 (1982).

Power Balance Curves and Ignition via Ohmic Heating Alone in an OHTE Device

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In this study a modified zero-dimensional power balance code is used to locate in the density-temperature plane the equilibrium curves where the plasma heating rate equals the cooling rate. Particular emphasis is given to the scaling of the energy confinement time: a semi-empirical linear behavior of the temperature with the current is considered and various geometrical scaling laws are investigated. Results obtained by extrapolating energy confinement times from current OHTE experiments in combination with a geometrical Alcator C-like scaling are presented for a range of device dimensions.

It is found that a pathway for the breakthrough from the ohmic heating to the fusion heating dominated region is achieved when the I/N parameter is about 10^{-14} A.m. Over a reasonable range of parameters, this result is fairly insensitive to the variations in the device dimensions. However, these calculations indicate that a larger plasma current is required for heating to ignition than is predicted in earlier reactor studies. The current requirement is relaxed after ignition.

SHERWOOD THEORY MEETING

Madison, Wisconsin

April 15 to 17

Modelling of Current Ramps and Sawtooth Oscillations on TEXT**D.W. Ross, W.H. Miner and J.C. Wiley*

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The transient behavior of plasma profiles during fast and slow current ramping in TEXT is investigated, and the initial current rise and sawtooth oscillations are re-examined. The work is motivated by recent experimental studies of these phenomena, in which data from the ECE radiometer, Thompson scattering, soft-X-ray measurements, loop voltage, and Mirnov oscillation monitoring are combined.¹ Fast current ramping, in particular, exhibits initially inward motion of the X-ray inversion radius and no skin effect in the temperature, together with large increases in the loop voltage and Mirnov oscillations. Simulations of both the fast current ramp and the initial current rise indicate that *extremely* large thermal transport, in addition to anomalous current penetration, is required to account for the observed temperature profiles and loop voltage. These studies can also shed light on the sawtooth-averaged theoretical models previously employed to describe steady-state discharges.² In those models, theories of anomalous transport³ were tested and found to yield fair agreement with the observed confinement scaling. But *ad hoc* anomalies had to be postulated to account for thermal losses from the inner (sawtooth) and outer ($q > 2$) regions. In the former, the classical skin time greatly exceeds the sawtooth repetition time, so that a true steady state cannot be reached. Thus, as in current ramping, by studying the temperature evolution during the sawtooth rise, we attempt to determine whether resistive anomalies are required.

¹The TEXT experimental staff, to be published.

²D.W. Ross, W.H. Miner, O.P. Pogutse, and J.C. Wiley, Bull. Am. Phys. Soc. **29**, 1394 (1984).

³*e.g.* B.B. Kadomtsev and O.P. Pogutse, in Plasma Physics and Controlled Fusion, 1984 (IAEA, Vienna, 1985) to be published.

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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

Ion Thermal Transport in the TEXT Tokamak**W.H. Miner, D.W. Ross, A.A. Ware and J.C. Wiley*

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Recent results from the TEXT tokamak experiment¹ have shown that the ion temperature is greater than the electron temperature in the outer region of the discharge. The difference is large enough to cause the spatial integral of the collisional energy transfer from electrons to ions to become negative. These ion temperatures were obtained through Doppler broadening of ambient impurity spectra. Spatial resolution was obtained by scanning the plasma with a rotating mirror to determine the position of the emitting ion. The electron temperatures were obtained from Thompson scattering.

When similar results were shown in both the TFR² and Pulsator³ tokamaks, Ware^{4,5} proposed several mechanisms which could explain this anomalous energy transfer from electrons to ions. Two of the mechanisms he suggested were the direct Ohmic heating of the ions⁴ and the neoclassical transfer of energy between the electrons and ions.⁵

The purpose of this paper is to determine whether these mechanisms can explain the electron and ion temperature profiles observed in the TEXT tokamak. This will be accomplished by including these effects in a transport code and simulating TEXT discharges over a range of discharge conditions. The simulation is run until steady state profiles for the electron and ion temperatures are obtained. The steady state profiles are then compared with the experimental results.

¹The TEXT experimental staff, to be published.

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³Wagner, F., Max-Planck-Institut fur Plasmaphysik Report IPP 111/52 October, 1979.

⁴Ware, A.A., Nucl. Fusion **21**, (1981) 623.

⁵Ware, A.A., Nucl. Fusion **21**, (1981) 631.

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Evolution of Twisted Magnetic Fields

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We have considered the equilibrium of force free magnetic fields bounded on two sides by conducting surfaces. We assume that each fieldline intersects both surfaces, and that the positions at which it does so are specified. This provides a model for a field which evolves quasistatically, in a perfectly conducting medium, driven by slow forced motions of the endpoints.

We considered the case of axisymmetric twists, compressions, or dilations of the endpoints about a magnetic axis. We derived exact equations for the equilibrium and obtained a solution in closed form for the flux surfaces and field in the long, thin limit where the twist per unit length is small. The function $\alpha \equiv \vec{J}/\vec{B}$ is a function of the endpoint constraints.

A stability analysis indicates that the twisted field becomes unstable to ideal $m = 1$ modes for an amount of twist which is small compared to the upper bound predicted by linear theory. The analysis suggests that if an equilibrium state exists for severely twisted fields, it is helical rather than axisymmetric.

Reference

E. G. Zweibel and A. H. Boozer, "Evolution of Twisted Magnetic Fields," PPPL-2189 1985.

Acknowledgements

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STABILIZATION OF FREE BOUNDARY KINKS BY EXTERNAL CONDUCTORS*

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The high beta performance of the PBX device at Princeton appears to be severely limited by MHD disruptive activities. While the nature of these disruptions are not fully understood we have focused on the ideal free boundary kink mode as being possibly responsible. Suppression of this mode could substantially enhance the stable nature of bean-shaped plasmas since such plasmas were previously shown to have strong immunity against ballooning and internal kink modes. We have suitably modified our computational capability to include the effect of discrete conductors outside the plasma and also to calculate the image currents on these conductors. The nature of these currents can be useful for tailoring the shape and structural configuration of the stabilizing conductors. In addition, calculation of the magnetic field at all, or selected, points in the vacuum region can be correlated with flux measurements in the PBX device.

Results for the $n = 1$ mode have indicated that discrete axisymmetric plates in appropriate positions can completely stabilize the free boundary kink. Inclusion of the secular terms in the magnetic scalar potential would further enable us to examine the stabilization of the axisymmetric modes by the external conductors.

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NEOCLASSICAL TRANSPORT THEORY IN THE BANANA-PLATEAU REGIME IN NONAXISYMMETRIC TOROIDAL PLASMAS*

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Since current stellarators are operated usually in the banana-plateau regime and there are few problems which have not been clarified in the collisional ripple plateau regime in a rippled tokamak, the neoclassical transport theory in the banana-plateau regime in a nonaxisymmetric torus [1] deserves further studies. We employ the moment equation approach to the problem without considering the external sources but including the heat flux effect. In contrast to the usual calculations [2] in a stellarator where an average over the helical ripple is performed so that a stellarator is approximated by an axisymmetric tokamak, the moment equation approach keeps the full nonaxisymmetric effects. This allows us to study the combined effects of the helical field and the toroidicity, and the radial electric field. Also since the particle flux has been self-consistently separated according to the flux-friction relations, we clarify the "nonaxisymmetric" contribution to the particle flux in the collisional ripple plateau regime in a rippled tokamak. The particle flux in a rippled tokamak is similar to that of an axisymmetric tokamak after the radial electric field is determined. However, in a stellarator, the helical field also contributes to the particle flux. The details depend on the relative magnitude of ϵ_h and ϵ_t , and l and m numbers. A simplified form of the parallel viscosity in the banana regime will be presented. This allows us to calculate the bootstrap current quantitatively in any nonaxisymmetric system.

The dynamical behavior of the electric field in an arbitrary nonaxisymmetric system is also considered. In general, the electric field cannot be determined separately from the flow velocity. Two coupled time dependent equations for any two of the following four variables (U_t , U_p , $U_{||}$, Φ'), where U_t , U_p , and $U_{||}$ are toroidal, poloidal, and parallel flow velocities, have to be solved to determine the radial electric Φ' .

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Murshed Hossain, ICASE, NASA Langley Research Center

Ye Zhou and George Vahala, William and Mary

ABSTRACT

In the numerical simulation of strong plasma or fluid turbulence it is impossible to achieve the necessary spatial or temporal resolution on present-day (or near future) computers. In particular, as the turbulence evolves, high wavenumber and frequency components of v , B , ... become excited. Since these high k, ω modes cannot be resolved numerically one must resort to some analytical modelling of these subgrid scales in order to calculate their effect on the evolution of the large-scale velocity and magnetic fields.

Initially, we are employing the dynamic renormalization group approach to model away the subgrid scales in both (k, ω) for Navier-Stokes turbulence, extending the ideas of Rose¹ and McComb². This approach does not require the existence of a spectral gap between the large-scale fields and the subgrid scales.

work supported by NASA and DOE.

¹H. A. Rose, J. Fluid Mech. 81, 719 (1977)

²W. D. McComb, Phys. Rev. 26A, 1078 (1982)

TRAPPED PARTICLES WITH FAVORABLE AND UNFAVORABLE DRIFT*

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If trapped particles move in the favorable direction,^{1,2} instabilities (drift, MHD, etc.,) may not be excited by the resonance of the trapped particles with waves. This concept is not particularly helpful for a low β plasma such that $\beta \lesssim 5\%$. For high β tokamak plasmas, the gradient of the magnetic field helps to reduce and finally eliminate particles in the unfavorable direction. Several new designs of tokamaks are assessed in view of this property of a high β tokamak.

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2. W. M. Tang et al., PPPL-2142 (1984).

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

HELICITY AND HELICITY INJECTION*

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A general definition of helicity is proposed,

$$K = \int (\tilde{A} + \tilde{A}') \cdot (\tilde{B} - \tilde{B}') dv,$$

where $\tilde{A}'$ is a vacuum field. This definition is completely gauge invariant in any geometry including those with $B_n \neq 0$ on the boundary and does not depend on any matching conditions at the boundary between plasma and vacuum regions, as the helicity in other formulations does. In addition, using this definition it is never necessary to compute fields outside the region of interest. Minimizing the magnetic energy with this helicity (an ideal MHD invariant) fixed yields $\tilde{j} = \lambda \tilde{B}$, but with the possibility of $B_n \neq 0$ on the boundary. This definition of helicity is applied to a preliminary study of oscillating field current drive (helicity injection) in tokamaks, RFP's and three spheromak designs, S-1, CTX, and MS.

*Work supported by DOE.

**FLOW OF PLASMA AND MAGNETIC FLUX TOWARD A WALL
WITH APPLICATION TO FIELD-REVERSED THETA PINCHES**

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The flow of plasma and magnetic flux toward a wall is examined in a slab geometry where the magnetic field is parallel to the wall. MHD flow is assumed and a quasisteady approximation is made which reduces the problem to a system of two coupled ordinary differential equations. Far from the wall the medium is a uniform plasma with a uniform imbedded field and moving at a speed, u_{∞} . The magnetic field at the wall is specified and is less than the field at infinity so that the direction of flow is toward the wall. The calculated behavior shows that a thin current sheath is present near the wall. Within the sheath the flow speed is brought to a halt, the temperature first rises and then falls to the wall value. The flow speed outside the sheath, was found to have the approximate dependence, $u_{\infty} \approx B_{\infty}/5\mu e \int n dx$ where $\int n dx$ is the instantaneous plasma inventory in the sheath.

These results have been applied to the field-reversal phase of a field-reversed theta pinch, during which the changing magnetic field near the wall sets up an outward flow of plasma and magnetic flux. In this application the outflow of magnetic flux is stopped when the magnetic field at the wall is equal in magnitude and opposite in sign to that in the center of the chamber. Further rising of the wall field causes the sheath layer to lift off the wall. Based on these analyses, approximate expressions are found for the total loss of magnetic flux during reversal, the total heat flow to the wall, and the maximum possible magnetic flux retained after reversal. These results are compared with previous time-dependent MHD calculations and with experimental results from the TRX-1 and TRX-2 experiments.

STUDY OF ICRF SPECTROSCOPY AS AN ALPHA PARTICLE DIAGNOSTIC*

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Energetic alpha particles are an integral part of a fusion plasma, and can both influence plasma behavior and serve as an indicator of the onset and development of ignition. This paper addresses the use of higher harmonic ($n \geq 3$) ion cyclotron (IC) emission and/or absorption as an alpha particle diagnostic. The emission and absorption coefficients for higher harmonic fast magnetosonic waves are calculated. The computations are done for both energetic alpha particles and background deuterium ions for TFTR parameters. Within a slab plasma model, the fast wave spectrum emitted by the alphas in a direction outward along a major radius is calculated, along with the power absorption as a function of the frequency of externally launched IC waves. The additional physics which should be included in an analysis of a more realistic (cylindrical) geometry is defined. Practical implementation of these ICRF diagnostic techniques is discussed.

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BALLOONING MODES IN FLUID DYNAMICS*

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ABSTRACT

Ballooning modes exist in classical Fluid Dynamics, and correspond to waves propagating along streamlines. Stability criteria, which are in fact related to such modes, were obtained before¹ for a special configuration by methods not used in Plasma Physics. We apply more familiar techniques² to the problem, and obtain stability criteria for more general configurations. Strangely, instabilities often grow only algebraically, and exponential growth may depend on the system having "shearless" streamlines. We modify our method developed for rotating plasmas² which required writing the ballooning mode equations in all possible rotating frames, so that the stability criterion can be obtained using one frame of reference only.

¹K. Eckhoff and L. Storesletten, J. Fluid Mech., p. 401 (1978).

²E. Hameiri and P. Laurence, J. Math. Phys., p. 396 (1984).

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RESISTIVE BALLOONING MODES IN HELICAL AXIS STELLARATORS WITH LONGITUDINAL MASS FLOW*

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The equilibrium equation for systems with helical symmetry and longitudinal mass flow is derived for cases with temperature constant on a flux surface. The incompressible resistive ballooning mode equation for systems with a coordinate of symmetry and rigid longitudinal flow is also derived. A reduced ballooning equation is obtained by an expansion in $\epsilon = ah \ll 1$, where a is the minor radius and h is the helical pitch. The magnetic field line curvature is a quantity of order ϵ^2 . Thus ignoring the effects of toroidal curvature and treating the system as helically symmetric is valid for $\epsilon^2 \gg \epsilon_t$, where ϵ_t is the inverse toroidal aspect ratio. An analytic solution of the ballooning equation is obtained in the electrostatic approximation and invoking the two-length-scale expansion for a model equilibrium with circular flux surfaces and a magnetic axis with dimensions comparable to the minor radius. In the small longitudinal velocity limit, the static mode width and growth rate scaling as one third the resistivity are recovered. However, for small growth rates and large longitudinal velocity, the interaction of the magnetic curvature and the centrifugal force with the pressure and mass density gradients that lie on the surface, respectively, determine the width of the mode. In this limit, the growth rates are driven by the interaction of the magnetic curvature and centrifugal force components due to the helical motion of the magnetic axis with the radial pressure and mass density gradients, respectively. These modes scale linearly with the resistivity at a reduced level.

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GYROKINETIC PARTICLE SIMULATION OF ION TEMPERATURE
GRADIENT DRIFT INSTABILITIES*

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A gyrokinetic particle code¹ has been developed to study the dynamic properties of ion-temperature-gradient-driven drift instabilities in a shearless slab system. In these simulations the background pressure gradients are held fixed to represent the "steady-state" profiles characteristic of realistic plasmas. The purpose of the investigation is to identify the mechanisms responsible for the nonlinear saturation of the instability and the resulting anomalous transport. The model uses the assumption that the electron density response is adiabatic for $k_{\parallel} \neq 0$ modes and, for the nonlinearly generated $k_{\parallel} = 0$ modes, it follows the ion density response. For the flat density gradient case ($\eta_i = \infty$), these approximations are supported by the agreement between the results from the present model with those obtained from a code using the full electron response (drift - kinetic electrons), where $\eta_i \equiv \kappa_{Ti}/\kappa_n$, $\kappa_{Ti} \equiv -T_i'/T_i$ and $\kappa_n \equiv -n'/n$. The ion nonlinearities included in the model are those associated with the $\mathbf{E} \times \mathbf{B}$ convection, the polarization density response, and the parallel acceleration.

For a system where the instabilities are dominated by modes with $k_{\perp}\rho_s = 0.4$ for $\eta_i = \infty$, $T_e = T_i$, and $\kappa_{Ti}\rho_s = 0.2$, saturation is observed to occur for $e\phi/T_e \approx 8\%$. This level is similar to those found in simulations of universal instabilities² with comparable inhomogeneities (i.e., $\kappa_n\rho_s = 0.2$). The ion thermal flux has also been observed in the simulation and appears to increase steadily in the linear phase and reaches a peak value of $\chi_i = 0.01 \rho_s^2 \Omega_i$ at saturation. It compares well with the quasilinear estimate based on the observed amplitude, frequency, and growth rate. In the fully nonlinear stage of development, the flux fluctuates rapidly with time and its time-averaged value is a factor of 2 to 3 lower than that observed at saturation. For a larger simulation system including modes with $k_{\perp}\rho_s < 0.4$, a turbulent state is found to result. However, the time - averaged ion thermal flux remains at the same level as the coherent case. As expected, a smaller value of η_i produces a lower saturation amplitude and, hence, a lower thermal flux. However, no appreciable difference has been observed between $\eta_i = \infty$ and $\eta_i = 4$. Theoretical interpretation of results will be presented.

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

EFFECTS OF LOCALIZED MODES ON ION HEAT TRANSPORT*

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The importance of collective modes in determining the effective ion thermal conductivity has been previously emphasized.¹ In Ref. 1, the dominant term in the radial ion heat flux for a collisionless plasma regime was shown to be proportional to $\langle\langle h T_i b_i K(b_i) |e\tilde{\phi}(r)/T_i|^2 \rangle\rangle$ and dT_i/dr where the double brackets indicate an average over wave vectors, $\tilde{\phi}(r)$ is the perturbed electrostatic potential, $K(b_i)$ is a monotonically decreasing function of the poloidal wavenumber parameter $b_i \equiv k_{\theta}^2 \rho_i^2 / 2$, $h(\eta_i)$ is an instability threshold function, and $\eta_i \equiv d \ln T_i / d \ln n$. By assuming that mode growth saturates when the fluctuating $E \times B$ velocity becomes comparable to the equilibrium diamagnetic (∇T) drift velocity, the simple relation $|e\tilde{\phi}(r)/T_i|^2 \sim (k_{\theta} r_T)^{-2}$ was obtained where $r_T(r)$ is the ion temperature scale length. This estimate of the fluctuation amplitude neglects the strong spatial localization of $\tilde{\phi}(r)$ that is expected to arise in a finite inhomogeneous plasma where the poloidal wavelength $2\pi/k_{\theta}$ is a nonnegligible fraction of the inhomogeneity scale length.² Two recent and complementary approaches to obtaining a quantitative description of the mode localization are those of Coppi *et al.*³ and Guzdar *et al.*⁴ We have incorporated results from these investigations into a 1-D transport code and have used it to simulate Alcator C discharges fueled by pellet injection and gas puffing. In addition, we have used analytic and numerical (shooting code) techniques to attempt the solution of the general boundary value problem for the fluctuation potential.

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

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A CLASS OF ANALYTICAL SOLUTIONS
FOR
REVERSED PINCH TYPE CONFIGURATIONS

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A class of screw pinch and reversed field pinch (RFP) type analytical equilibrium solutions of the straight nonlinear Grad-Shafranov equation has been found. The reversal in these solutions increases with β . Multipole as well as circular solutions are possible. Axial currents in these equilibria are always unidirectional. Examples will be presented.

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Monte Carlo Calculations in Elmo Bumpy Square*

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We have generalized the ORNL EBT bounce-averaged Monte Carlo code to work for the Elmo Bumpy Square (EBS) geometry. The neoclassical diffusion coefficients in EBS are expected to be about an order of magnitude smaller than in EBT because of better centering of the collisionless orbits in EBS. Furthermore, the asymmetry in the electric field is expected to be much smaller in EBS than in EBT,¹ thus, nearly eliminating the convective flow of low energy particles out of the confinement region along potential contour lines. We have used the Monte Carlo code to estimate particle lifetimes in EBS and compared these with estimated lifetimes in EBT. Because the EBS confinement is so much better than EBT, the Monte Carlo code requires large amounts of computer time in order to obtain good statistics on the loss rates. Preliminary indications are that the global confinement time of the cool population in an EBS with symmetric potential will be about two orders of magnitude better than in EBT with asymmetric potential, in keeping with the expected improvement based on analytic neoclassical diffusion coefficients.

* 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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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

**Nonlinear Dynamics of Magnetic Islands
in High Temperature Tokamak Plasmas****R. Carrera, R.D. Hazeltine and M. Kotschenreuther*

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The nonlinear dynamics of single helicity islands is studied by a kinetic theory appropriate for high temperature plasmas confined in a tokamak. The following length scale ordering is considered: $R \sim L_s > a > w \sim \Delta > \rho$ where R = major radius, L_s = shear length, a = minor radius, w = island width, Δ = tearing layer width and ρ = ion Larmor radius. This ordering permits one to solve the nonlinear drift kinetic equation by using techniques similar to those employed in neoclassical transport theory. Electron motion around the major toroidal axis is assumed to be nearly collisionless so that electron trapping effects enter. However, motion around the island is considered collisional. In the behavior of wide islands (in which the ions are magnetized) the variation of the potential on the modified surfaces of the reconnected field is important. It couples the island evolution equation with the condition for the relaxation of the current distribution. In the limit of high collisionality and thin islands the Rutherford result¹ is recovered. The poloidally varying component of the island electrostatic potential modifies the Rutherford island growth by inducing a perturbed bootstrap current.

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

A NUMERICAL STUDY OF FINITE GYRORADIUS EFFECTS
ON LINEAR TEARING MODES

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The role of tearing modes in the behavior of tokamak discharges cannot be over emphasized. The study of $m = 2$, $n = 1$ (where m and n are poloidal and toroidal mode numbers, respectively) tearing mode which has been cited as the cause of major disruptions in tokamaks has been a very active research topic. Recent studies have shown^{1 2} that the inclusion of finite ion gyroradius effects leads to a stabilizing influence. However, most of the treatments have focussed on the parameter regime in which the ion gyroradius ρ_i is much larger than the tearing layer δ so that δ/ρ_i can be used as an expansion parameter. We have developed a numerical scheme to study the stability of global tearing modes in the region of $\delta/\rho_i \sim 0(1)$ which complements the studies in the two regimes $\delta/\rho_i \ll 1$ and $\delta/\rho_i \gg 1$. We will present details of the numerical algorithm as well as parametric studies of the influence of finite ion gyroradius effects on global tearing modes.

*Work supported by DOE.

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TRAPPED-ELECTRON TRANSPORT VIA MICROINSTABILITIES*

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In this work, a nonlinear gyrokinetic formalism¹ has been extended to include collisions. Furthermore, by following the procedures of neoclassical theory,² we have developed a general expression for particle diffusion which includes "anomalous" flux given by

$$\Gamma = \oint \frac{dl}{B} \left\langle \int d^3v \frac{c \delta \mathbf{E} \times \mathbf{B} \cdot \nabla \psi}{B^2} \delta F_0 \right\rangle ,$$

where the angular brackets represent spatial averages over microscopic length scale. Based on this result and the common belief that magnetically trapped electrons can not average out this $\mathbf{E} \times \mathbf{B}$ drift (while passing electrons can), trapped electron transport coefficient in the collisional regime ($\omega_{be} > \nu_{eff} > \omega_*$) is studied for a specified electrostatic drift wave spectrum.

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KINETIC STABILIZATION OF THE INTERNAL TILT INSTABILITY (N=1 BALLOONING MODE)
IN FIELD-REVERSED CONFIGURATIONS

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We are applying a recently developed formalism to study the kinetic stabilization of the internal tilt instability in a field-reversed configuration (FRC). The internal tilt instability for FRCs is a global $n=1$ ballooning mode. Within MHD, FRCs are predicted to be very unstable to this mode. However, the mode has not been observed experimentally and ion kinetic effects are believed to be responsible for the apparent stability.

The formalism that we are using is effective for numerically evaluating kinetic effects on the stability properties of multidimensional Vlasov equilibria. The method uses a dispersion functional, which is a quadratic form in perturbation quantities, and is applicable to general multidimensional equilibria. Our form of the dispersion functional is exact for all types of equilibrium particle orbits and the kinetic part is expressed in terms of the Laplace transform of an autocorrelation function for particles moving along equilibrium orbits. This form of the dispersion functional does not involve resonant denominators and the number of orbits used for evaluating phase-space integrals that occur is not limited by available computer memory.

Our plasma model for these studies is the Vlasov-fluid model (collisionless ions; massless, pressureless electrons). For a particular Vlasov-fluid equilibrium appropriate to an FRC, we have used the MHD eigenfunction ξ as a trial function to calculate the kinetic growth rate versus $\bar{s}$. ($\bar{s}$ is a parameter which measures the number of local Larmor radii across the plasma.) For a range of parameters appropriate to current experiments, the growth rate is at least 30 times smaller than the MHD growth rate. This is consistent with experimentally observed lifetimes. The calculation is being extended to include self-consistent determination of the eigenmode.

SAWTOOTH OSCILLATIONS AND GAS PUFFING IN THE ZT-40M REVERSED-FIELD PINCH*

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The ZT-40M reversed-field pinch device at the Los Alamos National Laboratory exhibits large-scale sawtooth oscillations in the soft x-ray flux during high- θ discharges ($\theta \equiv B_\theta / \langle B_z \rangle \geq 1.55$). The sawtooth crash (abrupt decrease in the soft x-ray flux) is preceded by large amplitude $m=1$, $n=8-15$ magnetic perturbations and subsequent toroidal magnetic flux generation. The present work examines the rise time of a sawtooth oscillation via 1-D cylindrical transport simulations where the plasma-magnetic field configuration is assumed to evolve through a series of equilibrium states. During this phase, the global properties of the plasma can be simulated without a flux regeneration mechanism, in stark contrast to the low- θ case where such simulations are not possible due to the continuous generation of toroidal flux. The simulations indicate that the plasma diffuses to a $m=1$ tearing mode unstable state which leads to the experimentally observed sawtooth crash and associated flux regeneration.

In order to make the simulations match the experimental data, large gradients in the electrical conductivity profile were imposed. A series of experiments using pulsed discharge cleaning and gas puffing (to raise the plasma density) were carried out to determine if the apparent resistivity gradients were caused by either a temperature instability (analogous to the one leading to $m=1$, $n=1$ tearing modes in tokamaks) or an anomalous effect. These high density discharges did not exhibit sawtooth oscillations, and indeed looked more like the low- θ discharges with continuous toroidal flux regeneration. The most likely explanation for this behavior is that low density discharges have a significant on-axis slide-away population causing an effective resistivity gradient. Data concerning the drift parameter and where the sawtooth transition occurs will be presented.

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DRIVEN, FORCE-FREE, HELICAL, OHMIC, STEADY STATES*

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We have shown that a helical, force-free, magnetic-field configuration that is a simple linear superposition of a finite number of harmonics of the form, $\{\sin(m_i\theta + k_i z), \cos(m_i\theta + k_i z)\}$, must have a spatially independent value of current density/magnetic field strength. The best known example of such a field configuration is that of Taylor's minimum energy state.

It is well-known that the helical solution of $\text{curl } \mathbf{B}(r, m\theta + kz) = \lambda \mathbf{B}(r, m\theta + kz)$ yields the minimum energy state of Taylor in a cylindrical pinch configuration of radius a when $\lambda a = 3.11$, $ka \approx 1.25$ and $m = 1$. Evidence for this state is lacking in laboratory RFP experiments.

We have found necessary, analytic conditions on a single harmonic, single helicity, magnetic-field configuration in order to have a force-free, ohmic equilibrium. As a result, we have concluded that Taylor's helical state is not a steady state in the presence of resistive dissipation, no matter how small. Nevertheless, Taylor's state remains significant because it may represent the mean magnetic configuration of a turbulent state.

If, on one hand, one were to change k from Taylor's value, one would find regions in which a reversed, force-free, helical, steady-state can exist when the helical amplitude is above a critical threshold. [In fact, the helically-averaged value of $\mathbf{e} \cdot \mathbf{b}$ must be greater than $\mathbf{E} \cdot \mathbf{B}$ in the reversed-field region, where $\mathbf{e}$ ($\mathbf{E}$) and $\mathbf{b}$ ($\mathbf{B}$) are the fluctuation (mean) electric and magnetic fields.] Experimental observations indicate the presence of helical states with the allowed wavenumbers. On the other hand, if one were to change the azimuthal mode number away from the Taylor value of $m = 1$, one would find no ohmic, steady-state solution at any wavenumber.

We shall demonstrate magnetic flux plots for certain allowed force-free, constant- λ , helical, ohmic, steady states and the structure of the associated helical electrostatic fields. We shall touch upon their relevance to future theoretical RFP (and possibly stellarator) studies.

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SELF-CONSISTENT DYNAMO IN REVERSED FIELD PINCHES

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We consider self-consistent dynamos, generated either by local or global modes described by the resistive MHD equations. The dynamics of global modes, versions of which have been considered in Refs. 1 and 2, is shown to imply specific properties of the electric field $\langle \vec{V}_1 \times \vec{B}_1 \rangle$ generated by the fluctuations. These properties are used as constraints, in addition to a given external electric field, in minimising the rate of entropy production. The result is an equilibrium state, similar to a Taylor state, but with finite pressure gradients.

The equations governing local modes, used in Ref.3, are extended to include all components of the perturbed magnetic and velocity fields, as well as an exact pressure equation (thus curing an inconsistency in Ref.3, the results from which are corrected). The similarity arguments of Ref.3 are used to determine $\langle \vec{V}_1 \times \vec{B}_1 \rangle$. It is found that the α -effect vanishes in this case, but an additional effect due to fluctuations damps the perpendicular current. The equilibrium state maintained by such modes tends to have current mostly parallel to the magnetic field. The toroidal magnetic field decays exponentially from the center of the plasma and does not show reversal.

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Near Term Tokamak Ignition Experiments

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There are currently a number of options for a near-term, low-cost tokamak ignition experiment. Among these are Ignitor, LITE, ISP, and TFCX. In choosing which of these options to pursue, there are a number of complex tradeoffs — physics performance/risk, engineering risk/complexity, cost effectiveness, as well as the question of ultimate reactor relevance.

Here the physics performance and risk is discussed in detail. The likelihood of attaining ignition, limiting phenomena, and potential obstacles are evaluated. The viability of the devices for studying burn physics phenomena is compared, taking into account energy deposition or heat flux limits, ash removal, pulse length, maximum number of pulses, diagnostic access, and remote maintenance requirements.

The experimental scenarios are simulated in detail with the DDMAK time dependent transport code. The times required to ignite, feasibility of pellet refueling, control of the thermal excursions, and the feasibility of reducing toroidal field and current to study the beta-limit at acceptable fusion power are investigated.

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INTERACTION OF FAST WAVES WITH ENERGETIC PARTICLES IN A HIGH-DENSITY TOKAMAK*

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The application of fast wave (or magnetosonic wave) with frequency near the lower-hybrid frequency appears more suited for current-drive in hot, reactor-like plasmas as compared to using the slow wave for the same purpose.¹ However, the existence of fusion-generated alpha particles may be deleterious for current drive due to the fact that a large fraction of wave-energy may be absorbed by the alpha particles through cyclotron damping.² In this paper, we consider an injected spectrum of fast waves (with small parallel refractive index $N_{\parallel}$), its interaction with the ubiquitous random density fluctuations near the boundary and its absorption by electrons and alpha particles. Such an unified approach will help understand the dynamics of fast waves interacting with a high temperature reactor-grade plasma. Results will be presented regarding the effect of such processes on the distribution function of the energetic particles and their implications with respect to current-drive as well as the performance of the device.

*Supported by U.S. Department of Energy Contract No. DE-AT03-84ER53158.

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RIGOROUS BOUNDS ON PLASMA TRANSPORT*

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Previous attempts to treat transport in turbulent plasmas have relied on simplifying assumptions, such as those involved in statistical closure approximations, to circumvent the intractability of the governing dynamical equations. These assumptions are difficult to justify either theoretically or experimentally. Furthermore, closures such as the direct-interaction approximation present extreme computational difficulties when applied to the inhomogeneous problems characteristic of turbulence in tokamak plasmas. Here, an alternative approach to transport problems is presented which yields *rigorous upper bounds* on global transport quantities. This approach, which has previously been applied to certain problems of fluid dynamics,¹ is well suited to the study of inhomogeneous systems, such as confined plasmas. It leads to expressions for absolute limits on transport in terms of experimentally controllable parameters, such as boundary conditions, even in the case of strong stresses and nonlinear response. Moreover, these limits can be refined by further analysis based on the dynamical equations. The technique consists of deriving, from suitable moments of the dynamical equations, a certain flux functional $\Gamma\{\delta\psi\}$ of the fluctuating field $\delta\psi$. One then maximizes $\Gamma\{\delta\psi\}$ over a class of fields which includes as a subset all stationary solutions of the dynamical equations. It will be shown how this scheme can be applied to a variety of plasma transport problems. As a pedagogical example, a simple yet nontrivial calculation of passive advective transport is described in considerable detail. For application to the tokamak edge region, resistive drift turbulence is considered, using the equations of Wakatani and Hasegawa.² The analytic derivation of the relevant transport functional is presented. To solve the resulting Euler-Lagrange equations, a 3-D code³ has been developed and tested. Both the analytical and computational work can readily be extended to other instances of transport in strongly nonlinear plasma systems. Progress in exploring the edge turbulence problem is reported, and several additional examples of variational principles for plasma transport are given.

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³ The numerical technique is an extension to three dimensions of the method described by H. Greenside and W. M. Coughran, Jr., Phys. Rev. A **30**, 398 (1984). We are indebted to Dr. Greenside and to Dr. A. Bondeson for extensive discussions and help.

ICRF-DRIVEN RADIAL DIFFUSION OF ENERGETIC
TAIL IONS IN TOROIDAL GEOMETRY

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ABSTRACT

Radial particle and energy transport of the high-energy tail ions created by ICRF heating is studied for tokamak and EBT geometry. The lowest order distribution function for the tail ions is calculated in two dimensional velocity space. The localization of the particles near the resonance pitch-angle is analyzed in detail by defining a new pitch-angle variable or a boundary layer parameter.

The energy and pitch-angle contribution to radial transport is calculated explicitly, assuming that the gyroradius is much smaller than the minor radius in a tokamak geometry or the minor radius is much smaller than the major radius in an EBT geometry. It is found that the confinement time of the high-energy tail particles scale as $\tau_t \propto T_e^{3/2} n_R / \langle p \rangle$, where T_e is the electron temperature, $\langle p \rangle$ is the absorbed microwave power density, and n_R is the resonant ion density.

BIFURCATION THEORY FOR TEARING MODES

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MHD instabilities often evolve towards asymptotic ($t \rightarrow \infty$) states which may be static, stationary, or time-dependent. They correspond to stable nonlinear solution branches of the MHD equations. Considering a visco-resistive plane plasma slab with stabilizing conducting walls at distance $x = \pm d/2$, we use either the Lundquist number S or the ratio d/L_{eq} (with L_{eq} the equilibrium scale length) as bifurcation parameter. Restricting ourselves to solutions with helical symmetry we find the points where branches bifurcate from a static equilibrium and we show that these branches correspond to stationary tearing modes. In general only one of those branches is a stable solution, to which the system tends for $t \rightarrow \infty$. Using a numerical code we illustrate the parabolic character of the stable branch and show examples of stationary flow and field patterns far from the bifurcation point.

OHMIC IGNITION OF AN ELONGATED TOKAMAK

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Despite that many plasma heating methods have been studied, Ohmic heating remains amongst the most economic and best understood heating schemes. Also, plasma energy confinement for Ohmically heated discharges has so far been observed to be better than that due to auxiliary heating. Former studies of the Ohmic heating to achieve ignition have concentrated mainly on reversed field pinches which require much physics development, or low elongation, high toroidal magnetic field (B_T) tokamaks which present engineering difficulties.

In this presentation, we examine the Ohmic ignition condition for a tokamak with large elongation κ .¹ The principal effect of elongation on Ohmic heating is that the toroidal current density j is proportional to κB_T , at a fixed safety factor q . Hence Ohmic heating power is proportional to $\kappa^2 B_T^2$. Also the neoclassical ion conduction time is proportional to κ^2 .² Hence the device can be operated at a high density below the ion confinement turn over, giving relatively good electron confinement. Our main result is that the required toroidal magnetic field at the minimum power for ignition is B_T (tesla) $\cong 4.4 q A^{1/4} / a^{5/8} \kappa$, where A is aspect ratio and a (meters) is small minor radius. With the usual assumptions on energy confinement, Ohmic ignition is obtained for relatively modest machine specifications: for example, $a = 0.25$ m, $B_T = 6.3$ tesla, $\kappa = 5$, $A = 5$, and plasma current equal to 10 MA.

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SIMULATION OF ICRH

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ICRH is simulated numerically in order to study the production of anisotropic temperature distributions for magnetic mirrors. In particular, we investigate the parallel ion cooling¹ and perpendicular ion heating associated with ICRH. A 2-1/2 D electromagnetic particle code² is used to simulate a plasma in which ion cyclotron waves are excited by applying resonant driving currents outside the plasma boundaries. Strong perpendicular heating of the ions and a slight decrease in the parallel ion temperature are observed. In addition, strong heating of the electrons in both perpendicular and parallel directions is seen. Reasons for the electron heating and its implications will be discussed.

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Energy Confinement in a High Current Reversed Field Pinch**Z.G. An, G.S. Lee and P.H. Diamond*

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In present temperature and current regimes, the resistive interchange (g) mode is a good candidate for explaining anomalous transport and "edge" confinement in RFP. A temperature scaling of $T_e \sim I_p^2/N$ has been predicted using a nonlinear theory of g -mode turbulence. This result is in good accord with current experiment¹. However, a crucial underlying assumption in the theory is that electron behavior is non-adiabatic, namely $\rho \equiv k_{\parallel}^2 v_e^2 / \gamma \nu_e \ll 1$. Since $\rho \sim T^{5/3} n^{-2/3} B_{\theta}^{-2/3}$, it is likely that $\rho > 1$ in future RFP experiments. Furthermore, significant ion heating will likely occur because of anomalous processes and thermal equilibration ($\tau_{E\text{conf}} \gtrsim \tau_{E\text{eqil}}$ at high current). In such adiabatic electron regimes, ion pressure gradient driven (η_i) modes, which are destabilized by magnetic shear ($L_S/L_T \sim 0(1)$ in RFP), are likely to induce significant energy transport in the presence of rather flat RFP density profiles. In particular, g and η_i drives couple additively in RFP configurations. In this investigation we study a set of nonlinear equations for $\tilde{\phi}$, $\tilde{H}$, $\tilde{v}_{\parallel i}$, and $\tilde{\tau}_i$ ($\tilde{\phi} = e\tilde{\varphi}/T_e$, $\tilde{H} = (\tilde{n}/n_o - e\tilde{\varphi}/T_e)$, $\tilde{v}_{\parallel i} = \tilde{\mathbf{v}}_i \cdot \mathbf{B}/B$, and $\tilde{\tau}_i = \tilde{T}_i/T_i$), which describe the coupled nonlinear evolution of g and η_i modes². A renormalized theory is presented and the saturation level of the fluctuations is derived. Transport scalings are obtained, and their implications discussed. In particular, these results indicate that pellet injection³ is a potentially viable mechanism for improving *energy* confinement in a high temperature RFP.

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Neoclassical Scaling Law for Tandem Mirror Transport*

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A simple model for studying the confinement time scaling of neoclassical transport in a tandem mirror is presented. Ions are assumed to be lost radially by resonant-plateau or stochastic diffusion and electrons are lost out the ends, thus the model is appropriate to the strongly plugged regime of TMX-U operation. The radial fueling profile in the center cell is found to be an important factor in determining the self-consistent radial potential drop $\Delta\Phi$ and the resulting neoclassical confinement time τ_I . Simple analytical estimates predict the particle confinement time scaling law $\tau_I \propto (\Delta\Phi)^{-2}$ when $e\Phi/T > 1$ consistent with TMX-U observations. Recent refinements of the model to include temperature gradients will enable a numerical investigation of both the particle and energy confinement time scalings, as well as the radial dependence of τ_I .

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Plasma Flow Through Magnetic Mirrors*

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Recently a set of fluid equations has been derived which describes the transport of plasmas with anisotropic pressures along the magnetic field lines (1). This set is valid for collisional to weakly collisional plasmas. These new fluid equations are used to study characteristics of plasmas flowing through magnetic mirrors. Plasmas in various collisionality regimes are considered. Plasmas flowing with subsonic, sonic, and supersonic speed at the mirror throat are studied. The effects of the mirror ratio and the structure of the magnetic mirror on the flow is investigated. It is found that the pressure anisotropy, which is directly related to the plasma collisionality, flow velocity, and magnetic field structure, is a critical parameter in determining plasma flow through the mirror. For example, the density drop across the magnetic mirror is found to become more pronounced with increasing pressure anisotropy. Large anisotropy is also found to give rise to the formation of multiple bumps in the density and pressure profiles on the downstream side of the mirror throat. The results are compared with the conventional fluid equations with and without viscosity terms. It is found that the conventional fluid equations are only accurate for highly collisional systems.

* Work supported by the U.S. Department of Energy Contract No. P.A.-DE-AT03-80ER52062.

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SHERWOOD THEORY MEETING 1985

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Analytic Theory of Nonlinear $m = 1$ Island Growth**R.D. Hazeltine, J.D. Meiss, and P.J. Morrison*

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Sawtooth oscillations near the $q = 1$ surface in tokamaks are commonly ascribed to the growth of unstable tearing modes with unit poloidal mode number ($m = 1$). Because the constant- ψ approximation does not apply for $m = 1$, evolution of the resulting nonlinear magnetic island cannot be analyzed by the $m > 1$ prescription of Rutherford.¹ Furthermore, numerical experiments² show that $m = 1$ island evolution is characterized by exponential growth, far into the nonlinear regime, very different from the $m > 1$ result. The present coherent-island analysis is sufficiently general to treat both $m = 1$ and $m > 1$ perturbation structures. It also includes coupling to $m = 0$ components of the perturbation. When $m = 1$, it is found that the island structure displays criticality, changing its qualitative form when the perturbation amplitude exceeds a certain threshold, δB_c . The condition $\delta B = \delta B_c$ corresponds to the island width, W , equalling the linear tearing width. For $\delta B > \delta B_c$, one finds that the parallel current is nearly constant on island flux surfaces, as in the $m > 1$ theory. However, unlike the $m > 1$ case, one also finds that: (i) W becomes proportional to δB , rather than $(\delta B)^{1/2}$; (ii) the convective nonlinearity in Ohm's law exceeds the resistive term, and couples $m = 1$ to $m = 0$ components; (iii) the resulting nonlinear evolution displays exponential growth. If both the electrostatic and the electromagnetic potentials are assumed to be self-similar with respect to time, one can calculate the nonlinear growth rate. It is found to be 71% of the linear one, somewhat less than the 84% reduction-factor found numerically.

*Helpful discussions with Mike Kotschenreuther and Spilios Riyopoulos are acknowledged. This work was supported by the U.S. Department of Energy.

¹P.H. Rutherford, Phys. Fluids **16**, 1903 (1973).

²B.V. Waddell et al., Nucl. Fusion **16**, 528 (1976).

BALLOONING MODE STABILIZATION BY LARGE GRADIENTS
IN NORMAL MAGNETIC CURVATURE*

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In some systems localized analysis of the MHD equations may not properly describe the most unstable ballooning modes. Then the proper radial structure of the eigenmode must be determined numerically. I demonstrate the increased stability of nonlocal modes in one system, and ascribe this effect to gradients in the normal magnetic field curvature. Only MHD effects are involved, under the assumption of an ad hoc cutoff on short wavelength modes due to FLR effects.

Analytic work on the ballooning mode begins with a separability assumption for the radial eigenfunction:

$$B \xi_{\psi} = X(\psi, \dots) = A(\psi) \bar{X}(\dots; \psi)$$

The amplitude $A(\psi)$ varies rapidly with ψ , compared to the slow parametric variation of the infinite wavenumber solution $\bar{X}$ with ψ . The variation of $\bar{X}$ along field lines (i.e., the ballooning effect) depends on the field line curvature, particularly on the relative magnitudes of good and bad curvature. The localized analysis is formally valid only if $\bar{X}$ varies slowly over the width of the $A(\psi)$ peak. This width, for the most unstable mode, in turn depends on FLR effects which stabilize the most localized modes.

The system examined here is a multipole, which has the greatest possible variation in curvature effects. On one limiting surface the good and bad curvature cancel each other out and the ballooning mode goes over to an interchange mode. An internal separatrix causes infinite good curvature in the central region.

Equilibrium is computed on a floating orthonormal flux coordinate system, allowing grid line packing in the region of ballooning mode activity. I check ballooning mode stability by several methods, which determine the radial eigenmode structure with increasing validity.

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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

Cyclotron Resonance Induced Diffusion*

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The wave induced particle transport during the ion cyclotron resonance heating is studied for trapped particles in collisionless toroidal plasmas. The diffusion rate is determined by the radial shift of the guiding center turning point rather than the change in the width of the banana orbit used in earlier work.¹ Previously neglected non-conservation of the toroidal angular momentum P_ϕ caused by the toroidal wave component $E_\phi = E_\perp \sin \alpha$, $\alpha \cong \epsilon/q$ the angle between the magnetic lines and the toroidal direction, yields the leading diffusive contribution. The contribution from the induced changes in the magnetic moment μ is found to be less important in the short wavelength regime $kr \gg 1$, r = minor radius. The diffusion coefficient for near-Maxwellian distribution scales as

$$D \sim P_{rf} B^{-5} \epsilon^{-1/2} \lambda^{-2}$$

with P_{rf} , B , ϵ and λ the rf-power, the toroidal field, the inverse aspect ratio and the rf wavelength.

¹ K.W. Wang, G.J. Morales, Nuc. Fusion **23**, 481 (1983).

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

FORMATION AND HEATING OF A FIELD-REVERSED CONFIGURATION IN A COAXIAL SLOW SOURCE

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Plasma formation and heating in a coaxial theta pinch geometry are investigated using a recently developed computer code [1]. In these calculations, nonideal MHD equations are advanced on a transport time scale. For these slowly evolving (relative to wave transit times) solutions, plasma inertia may be neglected. Advancing the full MHD equations with a modified inertia leads to an efficient algorithm for following the desired slow phenomena. The initial operation of the University of Washington CSS experiment with a 20μsec. field rise is modelled. Plasma resistivity is taken to be a multiple of classical or is enhanced according to the Chodura model using the local drift parameter. Results of calculations with various resistivity are analysed to understand the variation of plasma length evolution with magnetic flux dissipation. Position variations associated with the relative timing of the inner and outer coil circuitry are also analyzed.

¹D. C. Barnes and D. D. Schnack, Bull. Am. Phys. Soc. 29, 1360 (1984).

⁺SAIC, La Jolla, California 92038.

NONLINEAR MULTIPLE-HELICITY CALCULATIONS OF IMPURITY-GRADIENT-DRIVEN TURBULENCE IN TOKAMAKS*

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The resistivity-gradient-driven turbulence [1] is a good candidate to explain tokamak edge fluctuations for moderate values of parallel electron thermal conductivity. This model can be extended to higher values of electron thermal conductivity when the effect of impurities is included. Rutherford [2] has shown that impurity-driven rippling modes could play an important role in the explanation of anomalous cross-field thermal transport, since they are not stabilized to any great extent by parallel electron thermal conduction.

A model including resistivity as well as Z_{eff} evolution has been developed. For normal tokamak profiles, the resistivity gradient is positive. When the Z_{eff} effects are included, it is clear that Z_{eff} -profiles with positive gradient will increase the destabilization while negative gradients will have decreased the effect. That is translated not only with modification of linear growth rates, but also with change in the nonlinear saturation levels of the fluctuations and diffusion coefficient.

We have studied numerically two different cases using Macrotor parameters. One with the gradient length scale of Z_{eff} $L_z = 0.40a$, and the other one with $L_z = -0.65a$. The gradient length scale of the Spitzer resistivity is $0.32a$ in both cases. The mean-square radial velocity at saturation changes (in normalized units) from 900 to 100, while was 400 for the case with constant Z_{eff} -profile. The results of these calculations confirm with the basic turbulent saturation mechanism proposed in Ref. [1] and agree with the analytical estimates [3] based on such dynamical mechanism.

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- * Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.
- [1] L. Garcia, P. H. Diamond, B. A. Carreras, J. D. Callen, IFSR 146 (1984).
- [2] P. H. Rutherford, "Physics of Plasmas Close to Thermonuclear Conditions," Vol. I, (1979) 143.
- [3] T. S. Hahm, P. H. Diamond, P. W. Terry, "Impurity-Gradient-Driven Turbulence and Particle Confinement in Tokamaks," this poster session.

SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

**Impurity Gradient Driven Turbulence and Particle
Confinement in Tokamaks****T.S. Hahm, P.W. Terry and P.H. Diamond*

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The results of analytical investigations of impurity gradient driven turbulence, which evolves from impurity driven rippling instabilities¹ are discussed in the context of modelling tokamak edge fluctuations and particle transport. Although usual rippling modes in pure plasma are stabilized by large parallel thermal conductivity $\chi_{\parallel}$, the presence of a significant impurity gradient renders the linear and nonlinear behavior of the modes insensitive to electron parallel dynamics. The results of this investigation indicate that: i) Linear growth rates are successfully approximated by Rutherford's formula¹ for most of relevant parameters. ii) Mode structures are such that the perturbed current j_z is negligible in the region where $\tilde{\varphi}$, $\tilde{\eta}_{sp}$ and $\tilde{Z}_{eff}$ are peaked off-center due to radial symmetry breaking both in the linear and nonlinear regime. iii) Nonlinear saturation occurs when the coupled effects of radial dependent impurity drag on ion flow and turbulent radial diffusion balance the impurity gradient drive. iv) At saturation, expressions are obtained for electrostatic fluctuation level $e\langle\varphi\rangle/T_e$, particle and impurity diffusion coefficients, magnetic fluctuation level $\langle\delta B_r\rangle/B_0$, and electron thermal conduction $\chi_{\perp e}$. v) The magnitudes and explicit Z_{eff} -dependences of these quantities lend useful insights into: a) the qualitative differences between metallic limiter and carbon (graphite) limiter discharges, b) 'density clamp' phenomena in neutral beam heated discharges, c) particle transport in H-mode regimes², and d) RFP edge confinement (in the presence of pressure driven modes).

¹P.H. Rutherford, in Physics of Plasma Close to Thermonuclear Conditions, edited by B. Coppi, et al. (Pergamon Press, 1981), Vol. I, p. 143.

²F. Wagner, et al., Phys. Rev. Lett. 53, 1453 (1984).

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

Quasilinear Theory of Cyclotron Instability
in the Presence of Electron Cyclotron Resonance Heating*

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A bounce-averaged relativistic quasilinear system of equations is derived to study the cyclotron maser instability of electrons heated by means of externally generated cyclotron waves. Perturbative solutions of the system of equations are used to determine the evolution of the cyclotron maser instability and the possibility of a stationary state.

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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

**Details of Tokamak Ballooning Stability
with Energetic Particles***

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The introduction of highly energetic trapped particles into a tokamak can stabilize MHD ballooning modes and allow direct access to the high-beta regime of second stability.¹ By considering a smoothed-out poloidal profile for the pressure of the hot particles, we find that the stabilization of ballooning modes is less enhanced than in the previous calculations in which a sharp profile was considered. For both the smoothed-out and sharp pressure profiles, we are able to derive an improved estimate of stability by means of a variational refinement of the Schwartz inequality used to obtain a lower bound for the trapped particle potential energy. Finally, we present analytical and numerical studies of how the stability boundaries are modified for ballooning modes that peak off the midplane.

¹ M.N. Rosenbluth et al., Phys. Rev. Lett. **51**, 1967 (1983).

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CALCULATION OF THE FULLY RELATIVISTIC DIELECTRIC TENSOR IN THE EC RANGE*

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Although relativistic corrections to absorption and emission in magnetized plasmas have long been known to be very important, it is only recently that the importance of relativistic effects in plasma dispersion has also been demonstrated [1]. It was shown that, for 90° propagation, relativistic effects drastically modify the cold plasma dispersion relation even at temperatures as low as 70 keV. We report here upon the development of a code to extend this work to all directions of propagation as well as more general electron distribution functions. The code is based upon a new representation of the plasma conductivity tensor [2] suitably generalized to anisotropic plasmas, and covers both arbitrary direction of propagation as well as the anomalous dispersion case when $n_{||}^2 > 1$. The paper will include a derivation of the underlying representation for the conductivity tensor, and discussion of the method of implementation. Preliminary numerical results will be presented.

¹D. B. Batchelor, R. C. Goldfinger, and H. Weitzner, Phys. Fluids 27, 2835 (1984).

²I. Weiss and H. Weitzner, to be published.

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Pellet Ablation in a Helical Reversed Field Pinch*

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In-situ pellet ablation experiments have been attempted before in tokamak devices with some interesting results.¹ Recently, there has been interest in doing in-situ ablation experiments on OHTE/RFP machines with the goal of increasing plasma density during a plasma discharge. Using an improved neutral ablation model,² pellet lifetimes are estimated to be ~ 3 msec for a frozen hydrogen pellet (0.35 mm in diameter and 0.80 mm in length) which ablates during current ramp up in the helical reversed field pinch, OHTE. The effects of high speed pellet injection on OHTE plasmas will also be theoretically discussed.

* Work supported by Phillips Petroleum Co. and GA Technologies Inc., under a Joint Research and Development Agreement (GA Ref. No. 01341).

¹ F. B. Marcus, D. R. Baker, and J. L. Luxon, GA Report: GA-A16060 (1980).

² S. E. Attenberger, W. A. Houlberg, and S. L. Milora, Bult. APS, 28 (1983).

**EFFECTS ON STABILITY
OF BALLOONING AND TEARING MODES
BY ECH IN THE DIII TOKAMAK***

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The Doublet III tokamak has performed a series of electron cyclotron heating experiments at 60 GHz with power levels up to 0.8 MW.¹ The power was launched from the high magnetic field side in the extraordinary mode. The toroidal field was $B_t = 2.14$ T and the plasma density, n (cm⁻³), was $1 \times 10^{13} \leq n \leq 8 \times 10^{13}$.

The discharges showed that (1) the confinement time deteriorated with power input in similar way to neutral beam heating, and (2) global heating occurred even when the central density was beyond the extraordinary mode cutoff.

It is clear that the ECH cannot be considered in isolation; its effects on the temperature and density profiles must also be investigated. In order to clarify the confinement issue we examine the temperature and current profiles produced by the ECH for stability against ballooning and tearing modes. We use a combination of ray-tracing and transport codes in this regime where the central density is below the cutoff density.

We also investigate the possible mechanisms for global heating by the extraordinary mode above the cutoff density.

*Supported by U.S. Department of Energy Contract No. DE-AT03-84ER53158.

¹K.H. Burrell *et al.*, I.A.E.A. London, 1984.

NUMERICAL RESISTIVE MHD SIMULATION
ON LONG TIME SCALES*

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ABSTRACT

A new method is presented for the numerical solution of the time dependent nonlinear resistive MHD equations on long time scales. The ultimate goal of the method is to eliminate shear Alfvén CFL time step restrictions so that simulations may proceed on the resistive time scale without using artificially low values of the magnetic Reynolds number.

The technique used here is analogous to the semi-implicit method of Harned and Kerner¹ for eliminating the fast mode CFL constraint. All of the terms in the original ideal MHD equations are advanced explicitly with a predictor-corrector method. However, unlike usual predictor-corrector methods, new higher order $[(\Delta t)^2]$ terms are added to the corrector equation. These new terms are treated implicitly. The coefficients for these new "semi-implicit" terms may vary with time and are determined from stability considerations. A spectral representation is used in the θ and z directions, and finite differences are used radially. Additional computation time (compared to an explicit scheme) is required for a single time step in order to solve a block tridiagonal matrix equation. However, this additional time is negligible compared to the time required for convolutions when several modes are present. Preliminary numerical results will be presented.

¹D.S. Harned and W. Kerner, J. Comp. Phys., to be published.

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THEORY OF FISHBONE OSCILLATIONS

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The observation¹ of "fishbone oscillations" in nearly perpendicular beam injected plasmas has led to investigate the excitation of internal $m^0=1$ modes in the presence of beam particle distributions. These modes are characterized by a "singular" (transition) layer where the mode undergoes fast variation, and an outer region where ideal MHD is valid. The theoretical effort made in order to explain the observations has taken two directions. One has focused on showing that the effects of trapped particles are important for the outer region, in altering the minimum value of the perturbed energy potential.² Our analysis instead³ has started from the observation that when the electromagnetic $m^0=1$ mode is driven near or past the condition of ideal MHD stability by the rising value of the plasma β parameter, it acquires a frequency of oscillation about equal to ω_{*1} (core-ion diamagnetic frequency), whose value, for typical PDX parameters, is consistent with that experimentally observed. Given this fact, one can explain the experimentally observed scattering process of the injected beam particles precessing at the magnetic drift frequency as a byproduct of the excited mode. Notice that this picture also explains the sawtooth events with a frequency of 4-10 kHz and phase velocity in the direction of the ion diamagnetic velocity (contrary to the reconnecting case), which were observed in PDX for plasma parameters near the $m^0=1$ marginal stability boundary, and which also involved large ion losses.⁴ Therefore, we have undertaken a comprehensive analysis of this mode, recognizing the key role that the transition region and the complete evaluation of the mode profile play in order to arrive at a consistent theoretical picture. A Fourier-space representation that includes the appropriate energetic ion gyro-radius effects is used.⁵

¹D. Johnson et al., Proc. IX IAEA, Baltimore, 1982; K. McGuire et al., Phys. Rev. Lett. 50, 891 (1983).

²L. Chen, R.B. White and M.N. Rosenbluth, Phys. Rev. Lett. 52, 1122 (1984).

³B. Coppi, Varenna Workshop on Plasma Transport (1982); B. Coppi, PPPL Workshop on Bean-Shaped and High- β Tokamaks, Princeton, April 1983; M. Velli, F. Porcelli and B. Coppi, Bull. Amer. Phys. Soc. 29, Oct. 1984.

⁴J.D. Strachan et al., PPPL Report 2165, Princeton, 1984.

⁵F. Pegoraro and T.J. Schep, Bull. Amer. Phys. Soc. 29, Oct. 1984, and Rijnhuizen Report 84/051, Nieuwegein, 1984.

NUMERICAL SOLUTIONS OF ICRF FIELDS
IN AXISYMMETRIC MIRRORS

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ABSTRACT

The results of a new numerical code called GARFIELD (Grumman Aerospace RF FIELD code) that calculates ICRF fields in axisymmetric mirror geometry (such as the central cell of tandem mirror or an RF test stand) are presented. The code solves the electromagnetic wave equation using a cold plasma dispersion relation with a small collision frequency to simulate absorption. The purpose of the calculation is to examine how ICRF wave structure and propagation is effected by the axial variation of the magnetic field in a mirror and for various antenna designs. In the code the wave equation is solved in flux coordinates using a finite element method. This should allow more complex dielectric tensors to be modeled in the future. The resulting matrix is solved iteratively, to maximize the allowable spatial grid, using alternating direction SLOR method. Results for a typical antenna array in a simple mirror will be shown.

THE APPLICATION OF LIE TRANSFORM PERTURBATION METHODS TO
HAMILTONIAN FIELD THEORIES*

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The method of Lie transforms has enjoyed great successes in applications to finite dimensional Hamiltonian systems. In this work, we extend the method to possibly noncanonical Hamiltonian field theories, and show that it is a natural generalization of Rayleigh-Schrodinger perturbation theory. In a finite dimensional phase space, a Lie transform is a near-identity canonical transformation, $z' = \exp(\epsilon \{W, \})z$, generated by a single scalar phase function, W . The technique is still valid in the continuum limit, where the generator W is now a functional of the field variables.

Several techniques for dealing with resonances are discussed. In particular, box quantization is a useful tool for discretizing modes so that the averaging process used in the Lie transform technique may be carried out unambiguously; once this is done, we may pass back to the continuum limit.

Applications to systems of interest in plasma physics such as the Zakharov equations, as well as several quantum mechanical examples are presented.

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MHD Stabilization of High β Mirror Plasma
Partially Enclosed by Conducting Wall.*

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An MHD formulation is used to study a wall stabilized high β mirror plasma with isotropic pressure. The stabilizing wall extends axially only a part of the distance between the mirror midplane and throat. We model this arrangement using a wall that approaches the plasma surface in the bad curvature region and is distant from the plasma in the good curvature region. A variational method is used to solve the equation in the distant wall region and an iterative method^[1] is used to solve the equation when the wall is close to the plasma. A jump condition is used to connect the regions of close and distant plasma-wall proximity. The results show that for a low mirror ratio case more conducting wall surface is needed for stability than in the high mirror ratio case. This agrees with the physical mechanism of the wall stabilization.

[1] Kaiser, T.B. and Pearlstein, L.D. UCRL-91320. (1984)

* Supported by D.O.E. Contract No. DE-AC02-78ET 51013.

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TEARING AND BALLOONING STABLE HIGH β TOKAMAKS *

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Maximum achievable β of tokamaks stable to both tearing and ideal MHD ballooning modes is studied for a plasma with a circular cross-section. Full toroidal and finite β effect is taken into account in the equilibrium and ballooning mode stability investigation. For simplicity, however, these effects are first neglected for the tearing mode. In optimization procedure, globally smooth profiles are preferred. Locally flattened pressure and current profiles are assumed to result from the quasilinear effect of ballooning and tearing modes. The resultant optimum β as a function of aspect ratio and the distance to an external conducting wall is presented.

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NONLINEAR INTERACTION OF DISSIPATIVE TRAPPED PARTICLE MODES
AND DRIFT WAVES WITH RF FIELDS IN THE ION CYCLOTRON RANGE OF FREQUENCIES*

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We study the nonlinear interaction of a coherent arbitrarily polarized electromagnetic wave in the ion cyclotron frequency range with dissipative trapped particle modes and drift waves. We show that trapped particle modes ($\omega \ll \Omega_i$, Ω_i is local ion cyclotron frequency) and low frequency drift waves ($\omega \ll \Omega_i$) can be stabilized if the driver pump electric field exceeds the critical value needed for suppression of their growth. Stabilization is a direct consequence of resonant nonlinear coupling to ion cyclotron harmonic sidebands. The influence of the RF field on diffusion induced by trapped particle modes and drift waves is studied and results are applied to mirror and tokamak environments.

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Flux Regeneration in ZT-40M at High Θ
and its Relation to the MHD Model*

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In this paper, the following will be shown:

1. Any toroidally asymmetric flux regeneration mechanism must arise from the $m=0$ component of the dynamics.
2. The flux regeneration mechanism in ZT-40M at high Θ is toroidally asymmetric.
3. $m=0$ single mode MHD instabilities always oppose flux regeneration.
4. $m=0$ magnetic perturbations driven nonlinearly by multi-helicity $m=1$ tearing modes can qualitatively produce asymmetric flux regeneration, but it is smaller than the symmetric component.
5. Hall effects may couple the spectrum in such a way as to enhance the asymmetric component of the toroidal flux regeneration mechanism.

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

NONLINEAR EVOLUTION OF COLLISIONAL DRIFT INSTABILITIES*

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The nonlinear evolution of collisional drift waves in a shear-free slab has been investigated by using gyrokinetic particle simulation techniques and also by solving, both numerically and analytically, model mode-coupling equations. In the simulation, which utilizes a scheme developed to study steady-state drift-wave turbulence,¹ a Lorentz collision model² is employed. The saturation amplitude of the instabilities and the resulting particle diffusion were observed to increase rapidly as a function of the electron-ion collision frequency, ν_{ei} . The dependence of saturation amplitude on ν_{ei} has been confirmed by numerical solutions of mode-coupling equations in which the collisions were represented by a one-dimensional diffusion model.³ Analytical studies, similar to those for the collisionless drift instability,¹ indicate that the dominant mechanism for saturation is the nonlinear $\mathbf{E} \times \mathbf{B}$ convection of the electrons. This process acts to nullify the phase difference between the density response and the potential, thereby shutting off the growth of the instability. An analytic expression for the saturation amplitude in terms of weak collisions has been derived. The result shows a dramatic increase in amplitude even for $\nu_{ei} \ll \gamma_\lambda \ll \omega_*$, where γ_λ is the linear growth rate. In the highly collisional limit, an upper bound for the saturation is found to be $e\phi/T_e \approx (\omega_\lambda/\Omega_i)/(k_\perp \rho_s)^2$, where ω_λ is the linear mode frequency. The corresponding quasilinear diffusion coefficient takes the well-known form of $D_{ql} \approx \gamma/k_\perp^2$, which compares favorably with the simulation results.

¹W. W. Lee, et al., Phys. Fluids, 27, 2652 (1983).

²R. Shanny, et al., Physics of Fluids, 10, 1281 (1967).

³A. Lenard and I. B. Bernstein, Phys. Rev. 112, 1456 (1958).

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

MODEL CALCULATIONS ON THE TILT STABILIZATION OF LARGE-ORBIT RINGS
BY ANGULAR MOMENTUM

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The angular momentum carried by the fast particles has been suggested¹ as cause for the observed tilt stability of large-orbit electron rings.² To test this hypothesis, we have performed a model calculation on the tilt stability of a rotating rigid ring carrying currents sufficient for field-reversal and an angular momentum equal to that of the fast particles; as in the case of the experiments, the ring is suspended in an axial field B_z and surrounded by a resistive medium. Calculating the resistive image currents in the medium and their influence on the ring motion, we find two possible modes depending on the strength of coupling of the ring to the image currents. They are a "fast" mode in which the ring precesses on a normal precessional time scale, and a "slow" mode in which case the ring axis is frozen by the image fields. In both cases though, the tilt angle between the axis and the external magnetic field will increase on a time scale equal to that of the resistive image currents, i.e. the rings are unstable with growth times comparable to the decay times of the resistive image currents. Applying this model to the experiments,² it appears that the angular momentum is not sufficient to explain the observed stability.

1. e.g. R. N. Sudan and P. Kaw, Phys. Rev. Lett. 47, 575 (1981); also T. K. Fowler et al., private communication.

2. e.g. D. A. Phelps et al. Phys. Fluids 17, 2226 (1974).

* Work supported by DOE Contract #DE-AS02-76ET53017

Nonlinear Ion Motion and Stochasticity Induced by ICRF
in the Center Cell of a Tandem Mirror*

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It is often the case that the antennae employed in experiments, where rf waves enhance MHD stability, produce more than one azimuthally propagating ion-cyclotron wave. We have studied the motion of ions in the center-cell of a tandem mirror in the presence of two azimuthally oppositely propagating left-hand polarized ion-cyclotron waves. Sufficiently far from resonance between the cyclotron frequency and the rf frequency the motion of ions is laminar and the ponderomotive drifts of the guiding-centers are derived. However, rough estimates of the parameters corresponding to the Phaedrus experiment at Wisconsin indicate that a substantial fraction of ions have stochastic motion with a decorrelation time that may be comparable to the grad B and curvature-drift time scales. Under such circumstances the rf is expected to affect the hydromagnetic stability of the machine in a way quite unlike that currently envisaged where the ponderomotive force essentially reverses the curvature drift of ions in a purely laminar fashion.

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

THE NONLINEAR BEHAVIOUR OF THE LINE TIED INTERCHANGE*

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As a model for the nonlinear evolution of the MHD ballooning modes we considered the tied gravitational interchange mode. Carrying out an expansion in which the aspect ratio of the plasma is ordered to be comparable to the strength of the gravitational field a reduced set of equations is obtained. A further expansion treats the margin of linearized instability as small leading to a nonlinear equation for the displacement ξ . This equation has a single nonlinear term which saturates the mode. The physics of the saturation process will be discussed and some special solutions of the nonlinear equation given.

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MONTE CARLO MODELING OF ICRH EXPERIMENTS IN STM AND TMX-U*

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The Monte Carlo Ion Cyclotron Code^(1,2) has been applied to identify the processes which control the heating, fueling and confinement of plasmas in two tandem mirror experiments. In the TRW Symmetric Tandem Mirror, ICRH is applied to the central cell to form high ion pressure plasmas ($\beta \leq 5\%$) to study the MHD stabilization properties of ELMO rings. Central cell ICRH in TMX-upgrade is used to reduce the collisionality of passing ions thereby reducing thermal barrier filling by Coulomb scattering.

The calculations show that for both experiments, the charge exchange rate is sufficiently faster than pitch angle scattering to preserve the high anisotropy induced by resonance heating in the distribution function. The axial ion density profiles are then peaked near cyclotron resonance. Assuming that the charge neutralizing background electrons are in pressure balance with an axial electrostatic field (Boltzmann), such density profiles lead to the formation of large axial variations of the electrostatic potential. These electric fields, in turn, play a critical role in regulating the fueling of the resonantly heated ion population. An accurate determination of the distribution of neutral gas⁽³⁾ becomes essential to the prediction of the properties of the final state.

Comparisons between Monte Carlo; Fokker-Planck⁽⁴⁾ and experimental results will be presented.

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* Work supported by US DOE DE-AC-03-79ET51017, TRW Subcontract to LLNL (#3441805) and TRW IR&D funds.

Rate Equations for a Tandem Mirror Plasma *

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We consider rate equations describing the evolution of the number and energy content of multiple groups of particles that are trapped in distinct (possibly overlapping) regions of a tandem mirror. The distribution function of each group of particles is parameterized with, for example, a temperature and a number density. The bounce averaged kinetic equation is then used to obtain equations for the evolution of these parameters.

In addition to collisional transfer of particles and energy from one group of particles to another, we find that changes in the electrostatic potential, ϕ or the magnetic field, B cause particles and energy to flow between particle groups that are trapped in overlapping regions. This results in terms in the rate equations for n and T that are proportional to $d\phi/dt$ and dB/dt . These terms directly couple the equations of evolution for the particle number and energy content to the equations of evolution for the fields ϕ and B . At low plasma pressures, when $\beta \ll 1$, the $d\phi/dt$ terms are most important, so we focus on these terms. The neglect of the $d\phi/dt$ terms when solving the coupled equations for the evolution of the particle number and the electrostatic potential is shown to lead to a non-physical instability.

The formalism described here is currently being implimented in the tandem mirror modeling code TREQ at LLNL. Preliminary results from this code will be presented.

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Nonlinear MHD Studies
of the CTX Spheromak*

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MHD simulations of the CTX gun-injected Spheromak¹ at Los Alamos National Laboratory are presented. The simulations are carried out in toroidal geometry with a three-dimensional, compressible, nonlinear, resistive MHD code. Cylindrical coordinates are used. The principal dependent variables are represented in a 1-D Fourier series:

$$U(r, \phi, z) = U_0(r, z) + \sum_{n=1}^N [U_{nc}(r, z) \cos n\phi + U_{ns}(r, z) \sin n\phi].$$

Because only low mode numbers are of interest, the toroidal (ϕ) direction is treated in a purely spectral manner; finite differencing is performed in the r and z directions.

The initial conditions consist of an equilibrium² known to be unstable to an $n = 2$ kink along with perturbations computed by an ideal linear stability code³. Simulations are performed for various values of magnetic Reynolds number S , various initial perturbation levels, various mesh sizes and mode numbers, etc. The 3D magnetic fields are fed into the TUBE code⁴, which traces magnetic field lines and outputs puncture plots in several poloidal planes.

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FRC DIFFUSION MODELLING: NEW APPROACHES

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In earlier work, we developed a one-dimensional numerical model of the theta pinch, which included microturbulence as well as other kinetic effects, and was well benchmarked with experiment. We successfully applied this model to particle confinement in the FRC by including axial pressure balance and appropriate radial boundary conditions.¹ In the present work, we have modified this 1-D code such that the communication between the outside and the inside region, inherent in the FRC, is exactly taken into account through flux tubes. We use non-flux coordinates so that the null point ($B_z = 0$) does not give any special difficulty. The new scheme for flux line equilibration is exact.

Secondly, a new approach to FRC modelling is proposed and discussed. In this approach, ions are treated as particles in 2-D (r, z) and electrons are treated as a fluid. MHD-like modes (e.g., $m = 1$ tilting, flute, or internal kink modes) are numerically simulated by a linear treatment of the θ (toroidal) dependence. Linear modes thus obtained are included in the original 2-D equation in a quasilinear fashion to determine the time evolution of θ -averaged quantities. This type of transport code should self-consistently calculate FRC transport including the effect of MHD-like instabilities, if they exist. In the stability analysis, ion kinetics are fully built in, to give an accurate picture of kinetic MHD behavior.

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RESISTIVE BALLOONING MODES DRIVEN BY ANOMALOUS TRANSPORT EFFECTS

BY

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ABSTRACT

The stability of resistive ballooning modes is examined in the presence of anomalous electron viscosity and radial thermal conductivity, using the Braginskii's two fluid equations. Choosing appropriate model terms to simulate these effects, a generalized set of coupled second order differential equations is derived in the ballooning space. By employing variational formalism as well as asymptotic matching technique, the analytical results are particularly discussed in two interesting frequency regimes, namely $S c_s / g R \ll |\omega| \lesssim c_s / g R$ and $|\omega| \gg c_s / g R$ where c_s is the sound speed, $g R$, the connection length and S is the magnetic shear parameter. Detailed calculations show that the anomalous thermal transport term excites new $m=1$ type resistive ballooning mode ($|\omega| \gg c_s / g R$) with large growth rate depending mainly on temperature gradient coupled fluctuations term. The excitation of $m=2$ type (or Δ' - driven) mode, on the other hand is found to be significantly influenced by electron viscosity and radial thermal conduction terms. The additional effect of parallel electron thermal conduction is shown to enhance the growth of Δ' - driven modes. The relevance of these results to currently observed electron heat transport in tokamaks will be discussed.

DETERMINATION OF THE AXIAL STRUCTURE OF THE
TRAPPED PARTICLE MODE IN TANDEM MIRRORS VIA HALO COUPLING*

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Abstract

The axial structure of the collisionless trapped particle mode has been approximately deduced via a variational principle as a rectangular function localized in the central cell (1). However, this ideal structure is unphysical in the sense that it implies infinitely large axial electric field at the ends of the central cell. There is no significant physical damping mechanism in the central cell which can truncate the short wavelength part of the spectrum of the ideal eigenfunction. The search for such a relevant physical damping mechanism has led to the halo coupling of the trapped particle mode. The radial coupling of the trapped particle mode to the halo plasma, can excite ion acoustic modes which are strongly damped at short wavelengths. This mechanism can easily smooth out the ideal rectangular structure. An approximate model of this halo coupling has been formulated and crudely solved. Approximate results indicate significant departure from the ideal rectangular structure and reduction of the growth rate. Other physical mechanisms which may be relevant for the Columbia Linear Machine will be discussed.

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Covariant Dynamics of Guiding-Center Plasma,
of Oscillation-Center Plasma, and of
Dissipative Plasma*

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A Lorentz-covariant approach to guiding-center theory has the advantage of incorporating electric fields in a natural way [1]. We formulate a relativistic Lagrangian action principle for a Vlasov guiding-center plasma coupled to self-consistent slowly varying electromagnetic field. The Noether algorithm yields the local (gauge-invariant) energy-momentum conservation law. The momentum law, in the non-relativistic limit, is of particular interest for fusion plasma. The perturbation by an eikonal wave is then treated by a covariant Lie transform, yielding the ponderomotive Hamiltonian and the linear susceptibility, i.e., a covariant form of generalized gyrokinetics.

Because Hamiltonian perturbation theory violates manifest gauge invariance, we re-examine the oscillation-center Lie transform for a free particle in a weak but general electromagnetic field, in terms of Littlejohn's differential-form perturbation theory [2]. The transformed Lagrangian action principle for waves and oscillation centers exhibits ponderomotive effects in gauge-invariant form.

To deal with dissipative effects, such as wave-particle resonance, in a covariant and self-consistent way, the dissipative-bracket formalism is generalized to be Lorentz-covariant. Local laws for energy-momentum conservation and entropy production are built into the algebraic structure [3].

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SHERWOOD THEORY MEETING 1985
Madison, Wisconsin
April 15 to 17

**Self-Consistency Constraints on Turbulent Electromagnetic
Relaxation and Transport in Collisionless Plasma***

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Turbulent magnetic fluctuation induced transport is commonly considered to be an important agent for confinement degradation in fusion devices. In this investigation we look beyond quasilinear theory to consider the constraints on collisionless turbulent relaxation imposed by improved treatment of self-consistency conditions.

The principal results of this investigation are: i) An improved (Lenard-Balescu) equation for the evolution of the electron distribution function in the presence of electromagnetic turbulence is presented. It is shown that for a collisionless drift-Alfvén system constructed using standard assumptions, electron magnetic transport effects vanish in a local analysis. This result is a consequence of accounting for self-consistency and momentum and energy conservation, and of the basic structure of the drift kinetic equation and is insensitive to the details of renormalized turbulence theory. However, we emphasize that this result is restricted to cases of stationary, collisionless turbulence. ii) A simple physical argument which sheds light on the result of i) has been constructed. It is shown that for *localized* (i.e., granular) phase space density fluctuations, the well-known ambipolarity constraint¹ on magnetic transport applies to *all* moments (including energy). Contact with "mixing length" intuition is made.

The relationship of these results to rotation damping, ambipolarity and various detailed instability mechanisms will be elucidated. Also, recent thermal transport² and dynamo³ models will be discussed in the light of this theory.

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

ABSTRACT FOR THE 1985 SHERWOOD MEETING

CURRENT-CONVECTIVE HEAT LOSSES IN REVERSED-FIELD PINCHES

by

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Recently, current-convective excitations have been recognized as a possible source of enhanced edge transport in reversed-field pinches.¹ The present nonlinear analysis is carried out on the basis of a two-fluid model including the effects of parallel current and thermal conductivity, electron compressibility, thermal forces, ion inertia and viscosity for time scales slower than the resistive diffusion rate across a perpendicular wavelength. Neglecting the effects of density gradients a set of mode-coupling equations is analyzed numerically (240-400 modes). The resulting edge heat diffusivity is found to be roughly equal to $D \approx cT/(eB) v_{\parallel e}/(l_T \omega_{ci})$, where l_T is the temperature gradient scale length in the edge, $v_{\parallel e}$ is the parallel electron drift velocity and ω_{ci} is the ion gyrofrequency.

The level of magnetic field fluctuations associated with these thermal excitations is found to be about 1% in the saturated state, indicating the possibility of thermal excitations as a cause of field line wandering in the edge of reversed-field pinches.

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* Permanent Address: Chalmers University of Technology, S41296, Gothenburg, Sweden.

STATISTICAL THEORY OF STRONG
LANGMUIR TURBULENCE

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The cubic direct interaction approximation is applied to the cubically nonlinear Schroedinger equation

$$i\partial_t E(x,t) + \partial_x^2 E + |E|^2 E - WE = 0$$

where W is the spatial average of $|E|^2$. This equation is one model of strong Langmuir turbulence and is, in fact, a generic equation which arises whenever a high-frequency wave is modulated by a slowly varying perturbation. The statistical theory is applied to this equation after spatial Fourier transformation to three, five, seven, and more modes. In the undriven, undamped case the theory often does a good job in predicting correlation times and final stationary amplitudes; the theory always evolves to a final thermal equilibrium stationary state. In the driven, damped case, the theory sometimes evolves to a stationary state with statistical properties similar to those which characterize the dynamical attractors.

ENERGY CASCADES IN CONVECTIVE TWO-DIMENSIONAL BENARD TURBULENCE

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Using our fully nonlinear, Cray-optimized spectral convection code ASTER [1] we study the energy cascade in the Rayleigh-Benard problem [2]. The interaction of the numerically calculated two-dimensional spectrum with the short wavelength modes outside the range of computation is taken into account using self-damping coefficients calculated by Direct Interaction Approximation (DIA) techniques. In the region beyond the Galerkin cutoff a simple Kolmogorov-type equation [3] represents the amplitudes of an isotropic spectrum, while the phase of the modes is not taken into account. Spectra calculated by this technique will be presented and applications of this method to fusion related problems will be discussed.

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MHD EQUILIBRIUM AND STABILITY OF CURRENT CARRYING TOROIDAL PLASMA*

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The major disruption in tokamaks may be interpreted as the violation of toroidal MHD equilibrium by certain symmetry breaking perturbations. The axisymmetric equilibrium β -limit in tokamaks is usually higher than the Troyon limit from the stability condition. The low- m helical modes which may be the kink or tearing modes are usually observed as precursors before the major disruption. Here we investigate the toroidal MHD equilibrium in the presence of helical perturbations induced by MHD instabilities. In order to facilitate the three dimensional problem, the averaging technique used in Stellarator¹ is applied, *i.e.*, by averaging the helical magnetic field and current induced by MHD instability over the deformed magnetic surface, and superposing these averaged quantities to the equilibrium magnetic field and current, and we will solve "renormalized" toroidal equilibrium to the first order of the inverse aspect ratio. Since the averaged magnetic field and current do not satisfy the Maxwell equation, they induce artificial force terms in the second order differential equation for the toroidal displacement.² The determination of the equilibrium β -limit in the presence of a single helical mode is underway by solving the renormalized differential equation for the toroidal displacement.

*Supported by U.S. Department of Energy Contract No. DE-AT03-84ER53158.

¹J.M. Greene *et al.*, Plasma Phys. **8**, 145 (1966).

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SHAPE OPTIMIZATION FOR SMALL ELONGATED TOKAMAKS

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We have been using the GA Technologies ideal MHD equilibrium and stability computer programs to investigate small elongated tokamak designs at variations in relevant design parameters.^{1,2,3} Such elongated tokamaks may achieve ohmic ignition at moderate toroidal fields.¹ For such tokamaks at moderate elongation we have determined an optimized β stable to ballooning modes. This has been done for a variety of shapes to include ellipses, racetracks, and beans. As expected, the bean-like shapes have higher β stable to ballooning modes but in order to obtain such shapes more complex tokamak designs are required. We have also studied internal kink stability and external kink stability for these shapes.

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**A MECHANISM FOR THE SPONTANEOUS GENERATION OF TOROIDAL
MAGNETIC FLUX IN A CONICAL THETA-PINCH**

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and

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A toroidal magnetic field of comparable magnitude to the poloidal field is observed to be spontaneously generated during the formation of a spheromak in a conical θ -pinch⁽¹⁾. Similarly, a significant net toroidal flux has been measured in an FRC after it was formed in a graded (conical) θ -pinch coil and translated into a flux conserving drift chamber⁽²⁾. Numerical calculations^(3,4) have shown that the Hall term can lead to the generation of toroidal magnetic fields during the early formation of FRC's, however, a simple analysis shows that by itself, the Hall term cannot account for the generation of significant net toroidal flux because both positive and negative toroidal fields are generated.

We find that an interaction of the Hall term and an anomalous plasma resistivity can lead to the generation of a net toroidal flux in these devices. Detailed numerical calculations using the 2-D MHD code MOQUI, predict a net toroidal flux of the same order of magnitude, but somewhat smaller than that observed experimentally in the conical θ -pinch. The predicted net toroidal flux for the FRX-C/T experiment is about an order of magnitude smaller than that observed experimentally.

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ICRH WAVE PROPAGATION EQUATIONS IN STELLARATOR CONFIGURATIONS*

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The ICRH wave propagation equations are expanded in a (ρ, θ, ϕ) flux coordinate system with the wave electric field $\vec{E}$ expressed as $\vec{E} = V \bar{\nabla} \ell_{np} + U(\bar{B} \times \bar{\nabla} \ell_{np})$. Because the mod-B surfaces in a 3D stellarator are hyperboloidal in shape, we model the device as a helically symmetric system (with ϕ the coordinate of symmetry). A reduced set of ICRH wave equations are derived by an expansion in $\epsilon = ah \ll 1$, where a is the minor radius and h is the helical pitch. The coefficients of these equations are simplified further by considering a model MHD equilibrium with concentric elliptical flux surfaces.

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MAGNETIC WELL PROPERTIES OF MODULAR STELLARATORS*

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ABSTRACT

The existence of a magnetic well in vacuum is generally considered a prerequisite for startup in any stellarator. Finite beta, current sheet representations of the modular stellarators investigated in this study have already shown the presence of a magnetic wells¹, but discrete coil representations do not. A concern arising from numerical simulation is whether the magnetic well found in current sheet representations could be an artifact of the approximation. Comparisons are presented here between vacuum magnetic field profiles from discrete coil, modular stellarators and those obtained from the finite beta, current sheet models predicting on-axis magnetic wells. These comparisons raise the question of the persistence of the magnetic well in the finite beta, continuous current sheet approximation to very small beta, or when the continuous current sheets are replaced by discrete coils.

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

**SYMMETRY-BREAKING HALF-COALESCENCE
IDEAL INSTABILITY ASSOCIATED
WITH $m/n=1$ TEARING ISLANDS***

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Using an initial value method, we have confirmed a new instability which may be involved in the collapse phase of the sawtooth instability. This mode is essentially an ideal mode with fairly large growth rate. The magnetic perturbation is up-down anti-symmetric, thus breaking the symmetry of the $q=1$ tearing island. The growth rate characteristics and the flow pattern predicted by Bussac *et al.*¹ are found to be in qualitative agreement with our computational results. Our equilibria are general $q=1$ magnetic island structures obtained by allowing the tearing mode to grow nonlinearly. The ideally unstable nature of these helical equilibria is confirmed through a linearized code treating the helical quantities as equilibria. For example, $\gamma = 0.13\omega_A$ for island full width $w/a = 0.73$, and $\gamma = 0.054\omega_A$ for $w/a = 0.61$ with vanishing resistivity and viscosity. Although the flow eigenfunction found by the code shows characteristics similar to the trial function used by Bussac *et al.*,¹ the details are not the same. The largest flow and magnetic perturbations are found near the x -point of the initial tearing island in the code. The current sheet forms just outside as well as inside the initial x -point. Even with finite resistivity and viscosity, the ideal δW calculated with the eigenfunction found in our code was negative, indicating the ideally unstable nature. The perturbed magnetic potential vanishes at the x -point of the initial tearing island despite the use of finite resistivity. The final eigenfunction in the code does not depend on the initial guess as long as the code is allowed to run for a significant multiple of linear growth times. This was clearly shown when the initial flow pattern 180 deg out of phase from the usual initial guess of the Bussac-type generated the final eigenfunction correctly. The nonlinear evolution shows a tendency toward a symmetric magnetic geometry. The effects of finite resistivity and viscosity are also explored.

*Supported by U.S. Department of Energy Contract No. DE-AT03-84ER53158.

¹M.N. Bussac *et al.*, Phys. Lett. **105A**, 51 (1984).

INDUCTIVELY DRIVEN CHANGES IN TOKAMAK PROFILES*

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Changes in profiles of current density, pressure and particle density are computed as a result of: (1) a rapid change in the cross-sectional shape of the plasma for circular to bean shaped; (2) adiabatic compression along the major radius followed by free expansion; and (3) rapidly heating the plasma to high beta. These profile changes are computed using the 1 1/2 D BALDUR upgrade transport code. Axisymmetric equilibria are computed in this version of BALDUR by using the steepest descent moments code developed by Hirshman.¹ Particular attention is paid to the profiles in the transition region between the highly conducting core of the plasma and the highly resistive annular region surrounding the plasma. As the core of the plasma pulls away from the limiter when the cross section is elongated, for example, low pressure and low current density plasma is pulled in, becomes heated and carries inductively driven current.

*Work supported by the US DOE Contract No. DE-AC02-76-CHO-3073.

¹S.P. Hirshman and J.C. Whitson, Phy. Fluids 26 (1983) 3553.

NEW APPROACH TO THE STUDY OF WAVES IN
COLLISIONLESS AND COLLISIONAL PLASMAS*

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The recently developed FLR-corrected collision operator¹ provides a powerful new method for the study of transport. The philosophy and formalism of this approach may be extended to the study of collisionless or collisional waves in plasmas. Several examples will be presented. The first example is a general equation for waves in a collisionless, inhomogeneous plasma. The kernel of this equation involves the so-called symplectic matrix $\partial Z_i(t)/\partial Z_j(t')$, which measures the effect on unperturbed orbits of a small displacement of coordinate Z_j at time t' on the coordinate Z_i at time t . The second example is a treatment of collisional damping of Langmuir waves. The calculation proceeds by perturbing about zero-order orbits derived via the Langevin equation, which describes single-particle motion under a random force. The key ingredient of the calculation is the ensemble-averaged wave phase $\langle \exp ik \cdot x \rangle$ seen by the particle along its unperturbed random orbit. The calculation agrees with previous results.^{2,3,4}

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Kinetic Theory and Simulation of Multi-Species Plasmas
in Tokamaks Excited with ICRF Microwaves*

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Advanced wave models used to evaluate ICRH in tokamaks typically use warm plasma theory and allow inhomogeneity in one dimension. Generally, the geometry is cylindrical with the radial coordinate corresponding to the major radius of the tokamak. The majority of these calculations neglect the fact that gyrocenters experience the inhomogeneity via their motion parallel to the magnetic field. These so called non-local effects of rotational transform and toroidicity can play a significant role in both the propagation and the absorption physics from the point of view of the wave dynamics. Moreover, insofar as the ICRH competes with collisional relaxation of the particle distributions it can induce neoclassical radial diffusion at the same order in ρ_p/a . Few authors deal with the inevitable effect wave damping must have on the underlying particle distribution function supporting the wave and the associated changes produced in the absorption. The most common approach is to use Maxwellian absorption rates.

We have attempted to advance the state of the art by developing a bounce-averaged Fokker-Planck quasilinear model which evolves the population of particles on more realistic orbits. Each wave-particle resonance has its own specific interaction amplitude within any given volume element; these data need only be generated once, and appropriately stored for efficient retrieval. The population of wave quanta present within the same volume element determine the overall strength of the diffusion. The wave-particle resonant interaction then serves as a mechanism by which the diffusion of particle populations can proceed among neighboring orbits. The local specific spectral energy absorption rate is directly calculable once the orbit geometry and populations are determined. The code is constructed in such fashion as to accommodate wave propagation models which provide the wave spectral energy density on a poloidal cross-section. In principle, accurate dispersion properties of the medium are also calculable, since the particle distributions are known, though more simplistic auxiliary models for wave propagation might be used as well within the context of a hybrid scheme. Information provided by the calculation includes the local absorption (and dispersion) properties of the medium which can then be exploited to evolve the wave field. Experimental diagnostics such as a scanning charge-exchange analyzer simulator are provided as a calibration tool with which to compare various wave propagation models with respect to a common set of experimental data.

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ANISOTROPY OF THE ELECTROSTATIC POTENTIAL IN EBT AND EBS*

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Here we develop an analytic expression for the experimentally observed poloidal asymmetry of the electrostatic potential, ϕ , in EBT and apply this expression to the ELMO Bumpy Square (EBS). The theory is motivated by the experimental observations that: (1) there are at least three disparate populations of electrons in EBT (bulk electrons, "warm" electrons, and the hot electron rings); and (2) ϕ scales with the "warm" temperature. A multiple fluid theory gives a hierarchy of equations — the lowest order equations being those of magnetic equilibria and radial transport. The new feature is the poloidal variation of macroscopic quantities — particularly those associated with the "warm" electrons. The poloidal variation in ϕ can be obtained from the warm electron transport equations provided one uses the dominant behavior of the other "fluids" to relate the asymmetry in ϕ to the asymmetry in the warm density via quasi-neutrality.

If one takes the isotropic limit for the warm electrons, one finds that the asymmetry in ϕ is proportional to the asymmetry in $\phi d\ell/B$. In EBT, the warm group was observed to be anisotropic. However, applying the more complicated anisotropic expression shows that in EBT the asymmetry in ϕ is relatively independent of anisotropy (because toroidal effects are uniformly distributed) and either expression is in accord with experimental observation.

For EBS the toroidal effects are concentrated in the corners and anisotropy is important. For EBS, the expression predicts a two order of magnitude reduction in the asymmetry of the potential — one order of magnitude occurs because of overall improvement of particle orbits ($\phi d\ell/B$) and the other order of magnitude occurs because trapped particle orbits are perfectly symmetric. This reduction in ϕ asymmetry is important because, as discussed in reference [1], it virtually eliminates convective losses for the bulk electrons which can be an order of magnitude greater than diffusion/conduction losses.

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

[1] J. S. Tolliver and C. L. Hedrick, "Monte Carlo Calculations in ELMO Bumpy Square, to be presented at this meeting.

EFFECT OF NONLINEAR COLLECTIVE PROCESSES ON THE
CONFINEMENT OF A PURE ELECTRON PLASMA

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ABSTRACT

For an electron plasma which is magnetically confined in a cylindrical field geometry, radial expansion occurs only if the angular momentum of the plasma changes. We discuss nonlinear collective processes by which perturbing, static, asymmetric fields can transfer angular momentum, but not energy, to the plasma and produce radial expansion. For example, the field asymmetry can act as a pump which excites daughter modes via the decay instability. Alternatively, the pump can drive a mode by induced scattering off of particles. The physical basis of these processes is quite general and may be relevant to other rotating plasma systems such as tandem mirrors.

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SHERWOOD THEORY MEETING

Madison, Wisconsin

April 15 to 17

Electrostatic and Magnetostatic Drift-BGK Modes*

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Recently, it has been shown¹ (in the case of a one-dimensional plasma) that self-binding BGK modes (holes) with phase velocity less than the thermal velocity are a most probable state¹ for localized, granular phase space density fluctuations. In the previous abstract,² it was noted that granularity of phase space density fluctuations imposes strong constraints on electromagnetic relaxation and transport in collisionless plasmas. Hence, it is important to study the structure of electrostatic and magnetostatic drift holes.

In this investigation, the structure of holes has been examined in the context of *simple* electrostatic and magnetostatic drift systems. The principal results are: (i) self-bound electron BGK drift-holes are possible for $k_{\parallel} u_{\parallel} > \omega_{*e}/1 + k_y^2 \rho_s^2$ ($u_{\parallel}$ = hole velocity). The (radial) hole structure is determined by the electron phase space density perturbation $\tilde{f}$ and the (ion) dielectric response. The electron hole structure has been characterized in terms of $\Delta v_{\parallel}$ (velocity width) and $\Delta x/\lambda \rho_s$ ($\Delta x \equiv$ spatial width, $\lambda =$ shielding factor) using a rectangular hole approximation. The resulting potential, radial electric field, velocity trapping width Δv_T , and self-energy have been calculated. In particular, since typically $\Delta v_T \gtrsim \Delta v_{\parallel}$, a self-bound state is likely. (ii) By determining the magnetic perturbation induced by the hole polarization current, a magnetostatic hole solution has been constructed. The magnetic perturbation scales as $(\delta B/B_0) \sim (u_{\parallel}/v_A) \sqrt{\beta} (\tilde{f} \Delta v_{\parallel})$. (iii) Self-trapping ion hole solutions have also been constructed. The resulting potential trapping width and self energy have been determined.

Investigations of hole interactions are in progress and will be reported on. The role of magnetostatic holes in self-consistent electromagnetic transport will be discussed.²

¹T.H. Dupree, Phys. Fluids **25** (1982).

²P.W. Terry, et al., "Self-Consistency Constraints on Turbulent Electromagnetic Relaxation and Transport in Collisionless Plasma" — adjacent paper.

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

TOROIDAL MHD EQUILIBRIUM DETERMINED BY LOW-FREQUENCY WAVE-DRIVEN CURRENTS*

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ABSTRACT

In order to solve the Grad-Shafranov equation to determine toroidal MHD equilibria in the conventional fashion, two arbitrary functions, the pressure, $p(\psi)$, and the diamagnetic function, $F(\psi) = RB_t$, must be specified. In the early work the functional forms of these functions were specified explicitly and somewhat arbitrarily.¹ In later work it has been more common to specify the safety factor profile, $q(\psi)$, instead of $F(\psi)$, but still with a somewhat arbitrary functional form.² This degree of arbitrariness in F , at least, can be removed if the equilibrium is sustained by steady-state rf current drive. In this case the current density consists of two distinct terms, $\underline{j} = \underline{j}^{NC} + \underline{j}^{QL}$. The neoclassical current, $\underline{j}^{NC}$, arises from the magnetic drifts of charged particles and is a known function of the plasma density and temperature profiles.³ The quasi-linear current, $\underline{j}^{QL}$, due to velocity space diffusion with an rf current driver, can also be calculated from a knowledge of the density and temperature profiles if the spatial deposition of the driver power is computed.⁴ Consequently a unique $\underline{j}$ exists, and it is possible to infer the $F(\psi)$ which is needed to solve for the MHD equilibrium, although this must be done in an iterative manner. The purpose of this paper is to present the derivation of the equation that determines $F(\psi)$ and the results of numerical calculations of MHD equilibria sustained by rf current drive.

1. D. Callen and R. A. Dory, Phys. Fluids 15, 1523 (1972).
2. J. F. Clarke, Oak Ridge National Laboratory report, ORNL/TM-5429, June 1976.
3. F. L. Hinton and R. D. Hazeltine, Rev. Mod. Phys, 48, 239 (1976).
4. T. M. Antonsen, Jr. and K. R. Chu, Phys. Fluids 25, 1295 (1982).

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SHERWOOD THEORY MEETING 1985

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Computer Simulation of Driven Alfvén Waves**J. Geary, J.N. Leboeuf and T. Tajima*

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PIC simulation techniques are used to investigate the dynamics of Alfvén wave resonance heating in a slab geometry. An antenna located at the edge launches a travelling wave. Several cases for homogeneous and inhomogeneous systems have been studied. The temporal evolution of the heating process yields flattening of the electron distribution function near the Alfvén velocity and the decline of the Alfvén wave amplitude. Our results indicate that the rate of electron heating is in good agreement with a Landau damping model.¹ Substantial ion heating at a level much higher than predicted¹ is observed as well. The ion heating is perpendicular to the magnetic field and is associated with the electrostatic fields present in the kinetic Alfvén wave.

¹A. Hasegawa and L. Chen, Phys. Fluids **19**, 1924 (1976).

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LORENZIAN ANALYSIS OF THE SELF-FILAMENTATION MODE

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A plasma immersed in a uniform magnetic field is unstable to current filamentation along the field if a cross field temperature inhomogeneity is present. The concomitant transverse magnetic fields bring into thermal contact unequal temperature surfaces and give rise to quasilinear effects. We examine the nonlinear behavior of this instability in the limit that the system may be reduced to the three lowest coupled modes, a la Lorenz.¹ It is shown that the three-mode system allows one nontrivial fixed point to which the instability saturates for low enough growth rates. Beyond a certain threshold, however, the fixed point is unstable and periodic behavior is exhibited. The three-mode results are corroborated with a many mode numerical study. Estimates of the anomalous transport are given.

Work supported by DOE.

¹E. N. Lorenz, J. Atmos. Sci. 20, 130 (1963).

GLOBAL EVALUATION OF MAGNETIC FIELD LINES^{*}

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Magnetic field line trajectories can be evaluated throughout a finite volume without field line integrations using the Hamiltonian properties of divergence-free fields.¹ A magnetic field can be described by a Hamiltonian $\chi(\psi, \theta, \phi)$ and transformation equations $\vec{x}(\psi, \theta, \phi)$ with $\vec{B}(\vec{x}) = \vec{\nabla}\psi \times \vec{\nabla}\theta + \vec{\nabla}\phi \times \vec{\nabla}\chi$. Physically $2\pi\chi$ and $2\pi\psi$ are the poloidal and toroidal fluxes and θ and ϕ are poloidal and toroidal angles. Given a field $\vec{B}(\vec{x})$, a canonical representation $\vec{x}(\psi, \theta, \phi)$ and $\chi(\psi, \theta, \phi)$ can be easily evaluated.¹ The most useful canonical representation is $\chi = \bar{\chi}(\psi) + \hat{\chi}(\psi, \theta, \phi)$ with $\hat{\chi}$ as small as possible. This means that the Fourier series for $\hat{\chi}$ contains only terms which resonate with $\kappa = d\bar{\chi}/d\psi$ and give the magnetic islands and stochastic regions. By considering an artificial time dependent field one can derive a set of first order differential equations in time which when integrated from zero to one, using standard numerical methods, canonically transform arbitrary canonical coordinates into the most useful canonical coordinates. The method is related to Lie perturbation techniques of Hamiltonian mechanics but eliminates the problem of small divisors through the use of $\hat{\chi}$ and is non-perturbative. The method can be extended Hamiltonians of any number of degrees of freedom.

¹A.H. Boozer, Princeton Plasma Physics Laboratory Report PPPL-2094R (1985).

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SPHEROMAK TILT-SHIFT STABILIZATION WITH PARTICLE RINGS

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We have developed a new method for obtaining necessary limits on the fast particle current required for tilt and shift stability of spheromak plasmas. A numerical code fully implimenting this method is now operational. We consider a rigid tilt or shift ($\delta q_\alpha = \delta\theta, \delta x, \delta z$) of the spheromak plasma with the fast particle component held fixed. The magnetic energy W_m of the full system is expressed in terms of the currents carried by the different components and the induction coefficients. The condition for tilt or shift stability is that the corresponding force $F_\alpha = \partial W_m / \partial q_\alpha$ have the opposite sign two the displacement. For stability of the tilt we need a fast particle current larger than $(\partial A / \partial \theta)(\partial L_{12} / \partial \theta)^{-1} (B_{ex} / c)$, where A is the axial projection of the area of the plasma ring and L_{12} is the plasma/fast-particle induction coefficient. At present, we have succeeded in generating self-consistent spheromak/fast-particle-ring equilibria which are tilt-stable and have spheromak/fast-particle current ratios of < 0.1 .

SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

Non-Axisymmetric, Sharp Boundary, Toroidal Equilibria*

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We examine the ideal MHD equilibrium of a sharp boundary, non-axisymmetric, stellarator, where the boundary is a vacuum magnetic surface. Suitable vacuum surfaces have been generated numerically with high accuracy using the Biot-Savart law for the magnetic field. We show that the solvability condition for sharp boundary equilibria take on a different form than that required for smooth pressure profiles with rational and irrational magnetic surfaces. In a sharp boundary configuration, a toroidal surface separates a constant pressure, current free plasma from an external vacuum region. Existence of equilibria in this state requires that two conditions be satisfied: (i) the plasma-vacuum interface be a magnetic surface for both the internal plasma magnetic field, $\mathbf{B}_i$, and the external vacuum magnetic field, $\mathbf{B}_e$, and (ii) pressure balance across the interface be maintained, i.e. $2P = B_e^2 - B_i^2$, where P is the plasma pressure. Given P and $\mathbf{B}_i$, the problem is to determine $\mathbf{B}_e$ on the interface for equilibrium. Writing $\mathbf{B}_e = \nabla\phi$, the pressure balance equation is observed to be the Hamilton-Jacobi equation, which is a first order, nonlinear, partial differential equation for the magnetic potential ϕ on the interface. The characteristics of this equation, which include the magnetic lines on the vacuum side of the interface, form a Hamiltonian system where the Hamiltonian function is $(B_e^2 - B_i^2)$. If ℓ_1 and ℓ_2 are two independent coordinates on the interface, the pairs (ℓ_1, p_1) and (ℓ_2, p_2) , where $p_i = \partial\phi/\partial\ell_i$, are conjugate variables. The Hamiltonian is thus quadratic in the momenta p_1 and p_2 . The existence of a single-valued solution for $\mathbf{B}_e$ arises if and only if Hamilton's equations yield single-valued solutions for p_1 and p_2 over the interface. This constraint on the momenta depends critically on the structure of the confining vacuum magnetic fields. In general, it is difficult to determine when the single-valued condition is exactly satisfied, as in all problems connected with integrability of classical Hamiltonian systems. Single-valued solutions for the momenta appear explicitly only if spatial symmetry is present. In the absence of symmetry, resonance phenomena affects integrability of the system, and numerical solutions or expansions are required to identify acceptable solutions. Perturbation studies of the Hamiltonian system, equivalent to expansions in terms of either small pressure or weak asymmetry, have yielded single-valued series representation for $\mathbf{B}_e$. Convergence of the resulting series is being explored. It is known from the KAM theorem and from investigations using renormalization techniques that solutions exist under suitable conditions. This method of equilibrium construction can be of practical value experimentally as one can determine how to design vertical field coils to counteract plasma shifts due to finite pressure.

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INVESTIGATION OF SATURATED TEARING MODES IN TOKAMAKS USING THE
RESISTIVE CHODURA-SCHLÜTER METHOD*

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Investigation is under way to find saturated magnetic islands in a tokamak. Our primary objective is to find such a state in a poloidal-divertor-configuration tokamak (e.g., the Wisconsin Tokapole II) to assess the effect of the divertor separatrix and noncircularity. To this end, a new 3-D computer code has been written to numerically advance the resistive MHF (magneto-hydro-friction) equations. This code differs from the standard Chodura-Schlüter code in that a small resistivity is introduced to allow rapid magnetic field tearing, and that all the dependent variables are Fourier-analyzed in the toroidal direction to facilitate an efficient mode representation. In order to handle the divertor separatrix, however, a finite difference representation is used in two cartesian components on a poloidal slice. The code is currently being tested in a simpler geometry without the divertor rings.

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Possible H-Mode Mechanism ?

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It has been frequently pointed out that tokamak confinement may improve dramatically at very high β , due to the magnetic well created by the plasma, and the resulting reverse precession of trapped particles (ref 1). Here we consider the possibility that we have already seen this phenomenon. Recall that the simple criterion for a magnetic well in a cylindrical tokamak is:

$$\beta_T > \epsilon$$

Now this formula was obtained from the following argument:

$$\mathbf{J} \times \mathbf{B} = \nabla P, \quad (\text{MKS})$$

but the diamagnetic term in $\mathbf{J} \times \mathbf{B}$ dominates in this case, so we can write

$$J_\theta B_T \approx \nabla P$$

and Maxwell's equations give

$$\mu_0 J_\theta = \nabla \times B_T.$$

Since we want ∇B_T due to J_θ to cancel the $1/R$ vacuum variation of B_T ,

$$\text{we take } J_\theta \approx B_T/(\mu_0 R)$$

and this then gives us a criterion for ∇P :

$$\nabla P > B_T^2/(\mu_0 R). \quad [\text{eq. 1}]$$

The usual argument then proceeds to assume

$$\nabla P \approx P/a.$$

For this case, however, we are interested in a local reversal of ∇B near the plasma surface. The idea is that the steep pressure gradient near the plasma edge is self-sustaining due to the absolute minimum- B it produces locally. If we insert numbers into eq. 1: $B_T = 1\text{T}$, $R = 2\text{m}$, we get that we require a pressure gradient of 5×10^5 pascals/m. If we assume $n_i = n_e$, this corresponds to 1.6×10^{24} eV/m⁴. Pressure gradients measured at the edge of PDX in good H-Mode discharges were in this range (ref 2), supporting the notion that in a very narrow region (< 1 cm wide) near the plasma surface, $d/dR(|B|)$ is indeed reversed.

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

Ref 1. Shoichi Yoshikawa (private communication), PBX Design Proposal

Ref 2. Kevin McGuire et al., IAEA 1984, London

STABILIZATION OF RESISTIVE KINK MODES FOR TOKAMAK
PROFILES WITHIN $q(0) < 1^*$

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The possibility of feedback-stabilizing the $m = 1, n = 1$ mode¹ introduces an opportunity to keep all resistive kink modes stable at lower q -values than were reported in Ref. 2. Our earlier profile studies are being extended to the range $q(0) \lesssim 1$, in which the modes $m/n = 2/3$ and $3/4$ become most important, while the condition for stabilizing $2/1$ and $3/2$ can be relaxed.

¹R. B. White, P. H. Rutherford, W. Park, and H. P. Furth, to be presented.

²A. H. Glasser, H. P. Furth, P. H. Rutherford, Phys. Rev. Lett. 38, 1977 234.

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SHERWOOD THEORY MEETING

Madison, Wisconsin

April 15 to 17

**Comparison of Heavy Impurity Injection and
Hydrogen Gas Puffing in TEXT****J.C. Wiley, D.W. Ross and W.H. Miner*

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Recent experiments on TEXT have compared a small hydrogen puff during the current plateau to a scandium injection at the same time. In each case an amount of material sufficient to raise the line average density by about ten percent is added to the plasma. The electron temperature near edge of the plasma decreases immediately in both cases after the injection. However, in the case of the impurity injection the central temperature also drops immediately while for the hydrogen case the temperature drop follows a delay consistent with an inward convective velocity on the order of that needed to model both the trace impurity injection experiments and the particle transport during gas puffing.¹ We have attempted to simulate these observations with several transport models similar to those investigated for gas puffing² and trace impurity injection.³

¹The TEXT experimental staff, to be published.

²J.C. Wiley, K.W. Gentle, W.H. Miner, O.P. Pugutse, and D.W. Ross, Bull. Am. Phys. Soc. 29, 1394 (1984).

³J.W. Wiley, W.H. Miner, Jr., and D.W. Ross, Sherwood Theory Conference, April 10-13, 1984.

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DISRUPTIONS DRIVEN BY EXTERNAL ELECTRIC FIELDS

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A previously-described (1,2) pseudospectral 3-D Strauss equations code is used to study disruptions in a current-carrying magnetofluid, with and without an externally-applied axial electric field. Rigid conducting walls form a square xy boundary, and periodic boundary conditions are assumed in the axial direction (z direction). Typical resolution is $64 \times 64 \times 32$ and the maximum Lundquist number is approximately 400. The dynamics are dominated by a helical current filament which wraps itself around the axis, parts of which can sometimes become strongly negative. A magnetic field-line tracing code has identified the presence of "magnetic islands". The ratio of turbulent kinetic energy to the total poloidal magnetic energy rises from very small values to values on the order of a few hundredths, and in the absence of the external electric field, executes "bounces" suggestive of sawtooth oscillations. In the presence of the external electric field, the first bounce is by far the largest, then the plasma settles into a non-uniform quasi-steady state characterized by a poloidal fluid velocity flow. The subsequent development of this fluid flow (which has the shape of a pair of counter-rotating bean-shaped vortices) depends strongly upon whether a viscous term is added to the equation of motion. (Since Braginskii viscosities are larger than the magnetic diffusivities for many devices of interest, inclusion of viscosity thus seems to be of importance. However, we do not have no-slip wall boundary conditions in the code yet.) Inclusion of viscosity tends to damp the flow and leads to pronounced subsequent bounces, though the first one remains substantially the largest. Highly regular and uniform "sawteeth" may require plasma processes not included in the Strauss approximation.

A second, related computation involves solution of the dynamical equations for a very low-order truncation of the Fourier-expanded Strauss equations. A three-mode (Lorenz-like) truncation displays interesting dynamical-systems behavior which often seems to have little to do with the full $64 \times 64 \times 32$ truncation.

- (1) J. P. Dahlburg, D. Montgomery, and W. H. Matthaeus, "Turbulent Disruptions from the Strauss Equations," 1984 preprint, to appear in J. Plasma Phys.
- (2) J. P. Dahlburg, D. Montgomery, and W. H. Matthaeus, Bull. Am. Phys. Soc., Ser II, Vol 29, 1239 (1984).

EQUILIBRIUM AND STABILITY OF HIGH-ORDER-MULTIPOLE TANDEM MIRRORS
AT LOW BETA*

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Interest in mirror machines with multipole symmetry of higher order than quadrupole has revived recently in hopes of reducing the size and cost of current quadrupole designs. Such configurations offer a potentially attractive alternative because of their near axisymmetry near the magnetic axis, which is advantageous from the points of view of transport and generation of parallel currents.

We study the guiding-center equilibrium and stability of tandem mirrors with multipole symmetry of general order ℓ in the low-beta and paraxial limits. The fluxline geometry is reduced to quadratures that can be evaluated exactly in the hexapole ($\ell = 3$) and octupole ($\ell = 4$). We deduce the structure of surfaces of constant pressure from the parallel-current constraint and find that the constant-pressure contours in planes perpendicular to the magnetic axis have a multiply-connected topology. A necessary condition for flute stability is derived from the guiding-center energy principle; the same condition is found to be required for preservation of axisymmetry near the axis.

Detailed numerical calculations are presented for the case of an octupole-anchor tandem mirror of TMX-U scale.

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FINITE β IN RFP RELAXATION

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Arguments are advanced to explain the observation of finite (sometimes large) β in otherwise nearly relaxed RFP plasmas. The Taylor magnetic free energy W_F , defined as the additional magnetic energy of a state above the energy of the fully relaxed (constant $\mu = \vec{J} \cdot \vec{B}/B^2$) state at the same magnetic helicity and axial flux, was computed directly. It was found that W_F is very much less affected by plasma pressure than by small changes in the spatial distribution of $\vec{\mu}(r)$. This fact suggests that pressure is not a major driving force in relaxation toward $\mu = \text{constant}$. Substantial pressure is therefore to be expected, up to where pressure-driven processes relax the nkT free energy.

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Alpha-Loss-Cone Alfvén-Wave Instabilities in a Sharp-Boundary Model of a Tandem-Mirror Central Cell *

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A sharp-boundary, cylindrical, DT plasma, surrounded by a vacuum annulus and a conducting wall is treated using the approach of Ref. 1. Three different branches of waves, namely the fast, hybrid, and Alfvén waves, with various azimuthal and radial mode numbers, are obtained. The alpha particle distribution is calculated by the methods of either Ref. 2 or Ref. 3. The alpha-driven temporal and spatial growth rates are formulated and computed numerically. Of the three branches only the Alfvén waves are unstable. We devote special attention to the dependence of the temporal growth rate on the parallel wave number. Our goal is to calculate marginal-stability boundaries for operation of the central cell of a tandem-mirror reactor.

¹K. Appert, J. Vaclavik, and L. Villard, Phys. Fluids **27**, 432 (1984).

²J. D. Hanson and E. Ott, Phys. Fluids **27**, 150 (1984).

³D. Anderson, H.-G. Gustavsson, H. Hamnén, and M. Lisak, Nucl. Fusion **22**, 403 (1982)

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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

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Alfvén Continuum with Toroidicity*

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The symmetry property of the MHD wave propagation operator is utilized to express the toroidal eigenmodes as a superposition of the mutually orthogonal cylindrical modes. Because of the degeneracy among cylindrical modes with the same frequency but different helicity resonant surfaces

$$\omega_o^2 = v_A^2(r_1)(n + m_1/q_1)^2 = v_A^2(r_2)(n + m_2/q_2)^2$$

the toroidal perturbation produces a zeroth order mixing of the above modes. The toroidal eigenmodes of frequency ω_o have multiple resonant surfaces, with each surface shifted relative to its cylindrical position and carrying a multispectral content. Thus a single helicity toroidal antenna of frequency ω_o couples strongly to all different helicity resonant surfaces with matching local Alfvén frequency. Zeroth order coupling between modes in the continuum and global Alfvén modes also results from toroidicity and degeneracy.

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

FRC TRANSPORT STUDIES UTILIZING A FLUX COORDINATE REPRESENTATION

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A one-dimensional, straight field line, flux coordinate based representation of the transport approximation, which includes the average beta condition, has been developed for the FRC. We utilize appropriately chosen dependent and independent variables so that no singularities appear at the magnetic field null radius (here a neutral line rather than a neutral point). These variables are adiabatic invariants in the absence of dissipation. This allows the salient features of the transport approximation (flux surface quantities) to be analytically, and thus exactly, incorporated into the mathematics. In addition, the boundaries both radial and axial, which move in physical space, appear fixed in this formulation (velocity is transformed away). This, in conjunction with the geometric approximation, produces a system of equations that although nonlinear is still relatively simple in its general structure. For example, when $\gamma = 2$ the plasma beta becomes an adiabatic invariant and the equation for radial force balance is reduced to quadrature.

Two quite general procedures for constructing solutions to this system of equations are presented. The first involves splitting off the axial contraction term (this appears as an Entropy source term) from the other dissipative terms (these involve resistivity, thermal conductivity, etc.) and integrating this piece with the axial contraction coefficient determined by the average beta condition. Radial and axial force balance are determined together after the explicitly time-dependent equations are numerically time-advanced. A computer code utilizing this approach has been developed and can provide numerical solutions for a wide variety of initial and boundary conditions and dissipative source terms of any general form.

The second method of solution is more analytically oriented and is complementary to the numerical procedure mentioned here. This consists in noticing that in the given representation solutions exist where the entropy as a function of normalized flux becomes stationary, and also, independent of the initial conditions. These solutions are fully time dependent in that the radial and axial boundaries and the internal and external flux may all have time dependence. Depending on the functional form of the transport coefficients, and which dominate processes are in balance, these solutions may simplify further. It is expected that these solutions, which appear stationary only with reference to special variables, will be solutions of an intermediate asymptotic form to which all initial conditions will be drawn on a sufficiently long timescale. These solutions are not separable owing to the adiabatic motion involved, unlike some instances where the solution to nonlinear diffusion equations may approach a separable form.

Work Performed Under the Auspices of the U. S. DoE.

Passing Ion Instabilities in
Tandem Thermal Barriers

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The concept of thermal barriers⁽¹⁾ has been introduced in Tandem Mirror plasma confinement devices in order to insulate the electrons in the central cell from those in the plugs. A depression in the electrostatic potential is created along the field line from local density minima that are maintained by some ion pumping the the barrier region. The presence of such a depression and the appropriate magnetic structure, however, allows a group of ions to pass from the central cell into the barrier region, traverse this region and then get reflected back into the central cell by the high potential hill that exists at the outer edge of the barrier. As a result of this counter streaming motion electrostatic and electromagnetic instabilities could arise which could adversely affect the function of the barrier.

In this paper we investigate these instabilities by examining the dynamics of the passing ions. Using flux conservation relations we obtain the distribution function of these ions as a function of the barrier potential, and mirror ratios relating the maximum and minimum magnetic field strengths in the barrier to that in the central cell. We find in the low temperature limit that deeper depressions in the potential - generally desirable for insulating the electrons in the two regions of interest - are less susceptible to electrostatic streaming modes while readily susceptible to electromagnetic instabilities. The effects of finite temperatures on these modes are also addressed.

1. D. E. Baldwin and B. G. Logan, Phys. Rev. Letters 43, 1318 (1979)

Line-tying of Hot Electron Interchange and Trapped Particle Modes*

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A model has been developed to explain a puzzling feature of the hot electron interchange (or trapped particle) modes which are observed in the axicell of the TARA tandem mirror, whenever α , the ratio of hot to cold electron density is too high. When the neutral density is high ($\sim 3 \times 10^{11} \text{ cm}^{-3}$), the observed modes always have high azimuthal mode numbers, $m \simeq 10$, although linear theory for $\omega < \omega_{ci}$ predicts that the lowest m modes will be the first to go unstable as α increases.¹ The discrepancy is resolved if line-tying is included in the theory. Our model describes bulk line-tying of an isolated axicell with non-emitting end walls; the radial dependence of the plasma parameters, and the contribution of the central cell and anchor, are ignored. In contrast to MHD interchange modes, which merely have their growth rates reduced by line-tying,² hot electron interchange modes can be completely stabilized by line-tying, provided the hot electrons have a spread of drift velocities. Furthermore, when ω is greater than the cold electron collision rate ν_e , the line-tying term is enhanced over the usual expression² by a factor of $(\omega/i\nu_e)^{1/2}$, because only a thin boundary layer of the electron velocity distribution can respond to the perturbation. Line-tying stabilization is more effective for low m modes, while the decoupling condition for the hot electrons¹ can more easily stabilize high m modes. The first mode to go unstable as α increases will be at intermediate m ,

$$m \simeq n_o^{2/5} \langle \sigma v \rangle^{2/5} \omega_{ci}^{4/5} m_i^{2/5} T_e^{-2/5} \nu_e^{-1/5} v_d^{-1/5} R_p^{-1}$$

where $n_o \langle \sigma v \rangle$ is the ionization rate, T_e is the cold electron temperature, v_d is the hot electron curvature drift velocity, and R_p is the plasma radius. For TARA axicell parameters $m \simeq 10$. We have² also considered a more realistic model in which the central cell, axicell, and anchor are included, and the mode amplitude can be different in each cell (a trapped particle mode). In this case a radial mode analysis is needed, because the neutral density in the central cell has a strong radial dependence.

¹H. L. Berk, Phys. Fluids 19, 1255 (1976).

²M. Wickham and G. Vandergrift, Phys. Fluids 25, 52 (1982).

INDUCTIVELY SUSTAINED TOROIDAL PLASMAS
WITH NESTED FLUX SURFACES*

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When the magnetic field in a plasma is time independent, the evolution of magnetic helicity in a volume element ΔV between two nested toroidal flux surfaces is

$$\frac{\partial \Delta K}{\partial t} = 2V_\phi \Delta \Phi - 2 \int_{\Delta V} \eta \underline{J} \cdot \underline{B} dV = 0 \quad (1)$$

where V_ϕ is the toroidal loop voltage, $\Delta \Phi$ is the toroidal magnetic flux in ΔV , and K is independent of the transformer induced vector potential, A_t :

$$K \equiv \int (\underline{A} - \underline{A}_t) \cdot \underline{B} dV \quad (2)$$

Each flux surface is defined by a poloidal flux function Ψ . The dissipation integral in Eq. (1) describes a linkage of currents similar to the linkage of fluxes in the definition of K , provided $\eta = \eta(\Psi)$.

Several theorems are derived regarding the existence of field reversal in the presence of nested flux surfaces. Reversal in the safety factor ($q = \partial \Phi / \partial \Psi = 0$) can only occur when the local (Ψ space) volume average of $\underline{J} \cdot \underline{B}$ also passes through zero. This is possible only when nonaxisymmetric helical field perturbations contribute to the rotational transform of field lines. Lower bounds for the nonaxisymmetric field components will be discussed.

The restrictions of Eq. (1) can be broken by tearing modes or nonlocal resistivity. Possible time dependent variations of this model will be discussed.

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

ANISOTROPIC PRESSURE HELIAC EQUILIBRIA

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ABSTRACT

The helical axis stellarator, Heliac, offers the advantages of large β and simplified engineering constraints. The latter is particularly true if circular coils are used. A Heliac with circular coils, however, is unstable at low β although it becomes stable at higher β where it encounters a second stability regime. Furth and Boozer have suggested the use of a hot electron layer to achieve the second stability regime in a Heliac. Under suitable conditions, hot electrons will not respond to MHD modes and their diamagnetic well could thus stabilize the plasma. Furthermore, the hot electrons would only be required until the background plasma reached the second stability regime; the heating power required to create the hot-electron layer could then be turned off. To address the issues basic to this concept in detail, an anisotropic pressure equilibrium code with helical symmetry has been written. Equilibrium results will be presented for various hot electron layer parameters as well as rudimentary stability measures such as well depth. Thorough localized stability analyses are planned, together with conceptual studies of optimized ECH techniques for efficient creation of the hot-electron layer.

ELECTRON ENERGY TRANSPORT IN TFTR^{*}

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The theory of anomalous electron thermal transport based upon the principle of "profile consistency" has been applied to TFTR Ohmic discharges, which have large impurity radiation losses and relatively high temperatures. The radiation losses enter the expected diffusion as a nonOhmic "source" term, and an additional term containing contributions from the neoclassical modifications to the electrical resistivity must also be considered. The resulting transport reproduces the experimental data reasonably well, but cases with large central sawtooth oscillations apparently experience some additional diffusion from the central region, beyond that occurring as a result of periodic flattening of the T , n , and j_z profiles. In these cases the electrical resistivity is assumed to be strictly classical inside the time-dependent $q=1$ surface to approximate the effects of an $m=1$ magnetic island.

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EFFICIENCY OF CURRENT DRIVE IN ROTAMAKS

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ABSTRACT

Rotamaks are compact toroids generated by rotating magnetic fields. Recent experiments have demonstrated that such configurations can indeed be produced in the laboratory [1]. A novel feature of the rotamak plasma is that large currents are generated across the ambient magnetic field with the help of a nonlinear ponderomotive force. This is in contrast to other conventional forms of rf current drive which use wave-particle interaction effects. The potential of this method for future applications is therefore of much interest. We calculate the current drive efficiency of rotamaks from first principles. We demonstrate that j/p (ratio of the dimensionless current driven $j = J/nev_{th}$ and the dimensionless power consumed $p = P/nT$) for rotamaks is much greater than unity. The ponderomotive force driven current sustenance scheme is therefore a highly efficient scheme and worth future exploitation in a wider range of applications.

Reference :

- [1] Hugrass, W.N. et al., Phys. Rev. Letters 44 (1980) 1976; Durance G. et al., Phys. Rev. Letters 48 (1982) 1252.

ELECTRON LANDAU ABSORPTION OF A REALISTIC SPECTRUM
OF LOWER HYBRID WAVES DURING CURRENT DRIVE*

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The absorption of a realistic spectrum of injected lower hybrid waves during steady state current drive has been studied in detail using a toroidal ray tracing code in conjunction with a parallel velocity Fokker Planck calculation (which includes an effective perpendicular electron temperature due to pitch angle scattering).¹ In typical steady state current drive experiments, the major portion of the injected lower hybrid wave power² is in the direction of the electric field drift of the target plasma ($v_{||} > 0$), where $v_{||}$ is the parallel phase velocity of the waves. However some fraction of the incident wave power (typically $\sim 30\%$) is launched in the opposite direction ($v_{||} < 0$). The positive current generation for $v_{||} > 0$ is found to result from a very flat plateau on the electron distribution function which extends from $v_{||} \sim 3v_e$ to $v_{||} \sim (10-15)v_e$. This plateau is maintained at high phase velocity due to weak tail damping of the injected waves. The plateau is maintained at low phase velocity by injected waves at high $v_{||}$ which have had their phase velocities reduced to $v_{||} \sim 3v_e$ by toroidal geometry effects.¹ The negative current generation is found to be typically less than a fourth of the positive current and results from a plateau which extends from roughly $3v_e$ to $(10-15)v_e$. However the plateau is quite sloped because of the smaller amplitude of the injected waves at $v_{||} < 0$. This results in strong tail damping of waves at high $v_{||}$ and a subsequent reduction in the RF current. This scenario for wave absorption has been studied at different toroidal magnetic fields and relative waveguide phasings for parameters relevant to Alcator C and PLT.

¹P.T. Bonoli, R. Englade and M. Porkolab, Proc. of the Fourth Int. Symp. on Heating in Toroidal Plasmas (Int. School of Plasma Physics, EUR-9341-EN, 1984) Vol. II, p. 1311.

²M. Brambilla, Nucl. Fusion 16, 47 (1976).

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

Wall Stabilized Tandem Mirror Reactor Study*

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We consider a tandem mirror reactor in which both the central cell and axicell are stabilized to low frequency, $m = 1$ azimuthal mode number modes by the presence of a wall that is located in close proximity to the plasma. Higher m modes are stabilized by FLR effects.^[1] A bumpy central cell field is used to optimize the central cell stabilization. The influence of realistic radial wall locations is investigated. Using detailed particle and power balance modelling we show that this scheme can produce tandem mirror reactors with very high wall loading, low recirculating power (high "Q") and short central cell lengths.

1. J. Kesner, "Wall Stabilized Tandem Mirror Reactors," to be published in Nuclear Fusion.

* Work supported by U.S. D.O.E. Contract No. DE-AC02-78ET 51013.

THE EFFECT OF RUNAWAY ELECTRONS
ON THE TEARING MODE

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and T.K. Chu, PPPL.

The $m = 2$ tearing mode is analyzed using a kinetic theory. The analysis is carried out using two different models for the equilibrium plasma current. In the first model a drifted Maxwellian electron distribution describes the equilibrium current, while in the second model the current is described by an electron beam on the tail of a Maxwellian distribution. The second model represents a current composed primarily of runaway electrons. In both models the equilibrium current profile is held constant. It is shown, both analytically and numerically, that in certain parameter regimes the $m = 2$ tearing mode is stabilized when the runaway electrons carry the total current. In the presence of runaway electrons, the real frequency of the tearing mode is shifted from the electron drift frequency, ω_{*e} , to slightly above ω_{*e} . The shift in mode frequency above ω_{*e} indicates that more of the available energy must be utilized to sustain the plasma particle oscillations which stabilizes the tearing mode. A comparison to experimental observations is also presented.

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ON THE IGNITION CRITERION FOR TOKAMAKS*

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A drift wave turbulence model has been shown to account both qualitatively and quantitatively for the anomalous electron thermal conductivity contribution to tokamak confinement scaling results. The present work applies the same model to an ignition tokamak. Four findings emerge: First in common with present ohmic heating experiments, a tokamak near ignition will be in the collisional drift wave regime where $v_{eff} > \omega^*$. Second, the energy loss rate predicted by collisional drift wave turbulence increases more rapidly with temperature than the D-T fusion reaction cross-section. Consequently, ignition is easiest to achieve at a low temperature $T \approx 6$ keV where fusion energy production has just exceeded Bremsstrahlung losses. Third, the ignition criterion is

$$[\beta(0)]^2 \left(\frac{B}{10T}\right)^6 \left(\frac{a}{1m}\right)^{2.5} \left(\frac{R}{1m}\right)^{1.5} > \left(\frac{.70}{q_L}\right)^2 \alpha_n^2$$

where α_n determines the flatness of the density profile via $n = n_0 (1-r^2/a^2)^{\alpha_n}$. Typical parameters for an ignition margin of 2 are $n_0 = 1.5 \cdot 10^{15} \text{ cm}^{-3}$, $B = 8T$, $a = 1m$, $R = 3.5m$, $q_L = 3.5$, $T = 6 \text{ keV}$, $\alpha_n = 0.5$. Fourth, the energy runaway time is short ($\approx 0.2 \text{ sec}$), so that a thermonuclear driven thermal runaway will occur in the region near the magnetic axis where confinement, according to both experiment and the drift turbulence model, is excellent apart from sawtooth and/or internal kink processes. Because the drift wave turbulence model does not account for this (thermal conductivity is assumed to be very high inside $q = 1$), our ignition criterion is conservative.

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MAGNETIC SURFACE QUALITY*

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We illustrate the concept and use of the magnetic field line Hamiltonian, $\chi(\psi, \theta, \phi)$, in the study of magnetic surface quality and island formation by a study of an infinite cylinder with given analytic helical fields. The magnetic field has the form $\vec{B} = \vec{\nabla}\psi \times \vec{\nabla}\theta + \vec{\nabla}\phi \times \vec{\nabla}\chi$, where ψ is the toroidal flux, and θ and ϕ are the magnetic poloidal and toroidal angles respectively. The Hamiltonian $\chi(\psi, \theta, \phi)$ is found by solving the differential equation

$$\frac{\partial \chi}{\partial \xi} = 2\xi \left(\vec{B} \cdot \left(\frac{\partial \vec{x}}{\partial \phi} \times \frac{\partial \vec{x}}{\partial \xi} \right) \right) / \left(\vec{B} \cdot \left(\frac{\partial \vec{x}}{\partial \xi} \times \frac{\partial \vec{x}}{\partial \theta} \right) \right)$$

$$\frac{\partial \xi_0}{\partial \xi} = 2\xi / \left(\vec{B} \cdot \left(\frac{\partial \vec{x}}{\partial \xi} \times \frac{\partial \vec{x}}{\partial \theta} \right) \right)$$

$$\xi = (\psi)^{1/2}, \quad \xi_0 = (\psi_0)^{1/2}$$

The transformation equations $\vec{x}(\psi_0, \theta, \phi)$ define approximate magnetic coordinates ψ_0, θ, ϕ and are obtained from field line integrations. This method is found to be more robust with respect to the evaluation of small Fourier coefficients than an earlier method based on the evaluation of $\vec{B} \cdot \vec{\nabla}\psi$. For illustration we show the $n/m = 1/4$ islands formed from the beating of $m = 2$ and $m = 6$ helical fields. From the computed $\chi_{1,4}$ we then reconstruct the magnetic field line by integrating

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

The width of the islands predicted by $\chi_{1,4}$ is in excellent agreement with that found from Poincare plots where the number of field periods needed to complete an island is given by $1/l_h$, where l_h is the transform in the helical system.

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SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

April 15 to 17

Impurity-Ion Acoustic Instability as the
Cause of Sawtooth Disruptions*

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In previous work¹ it was shown that for Tokamak discharges with $n_z Z^2 \gg n_i$ a catastrophic loss of ambipolarity (or poloidal equilibrium) occurs at a critical value of T_{eo} giving an $m = 0, n = 0$ disruption. The predicted values of both T_{eo} and $V_\theta [\equiv (B_\theta/B)V_\parallel - E_r/B]$ agree with such experiments. Also, although the above theory is inapplicable, even low Z_{eff} ohmically heated discharges satisfy the predicted relationship $V_\theta \simeq (B_\theta/B)v_{Tz}$, if V_θ is assumed given by $\omega_{m=1} = V_\theta/r$. Here it is shown that when $V_\theta \simeq (B_\theta/B)v_{Tz}$ the distortion of the ion and electron distribution functions due to neoclassical effects is just that required to turn off the ion and electron Landau damping and allow an impurity ion acoustic mode. Also, if the instability is driven initially by the electron current, it will develop in a catastrophic manner since the nonlinear effect on the trapped ions and electrons resonant with the wave is to increase V_θ and hence the growth rate until with $V_\theta > (B_\theta/B)v_{Tz}$ the poloidal rotation also drives the mode. Assuming $n' \equiv \partial n / \partial r$ is small, but allowing for the T'_i needed for the ion heat conduction the neoclassical condition for $V_\theta = (B_\theta/B)v_{Tz}$ in the plateau regime with low Z_{eff} in

$$2.5 \left(\frac{m_e}{m_i} \right)^{1/2} \left(\frac{T_{eo}}{T_{io}} \right)^{1/2} \frac{n_{eo} e E_\phi}{m_e \nu_e} = n_{io} v_{Tz} - \frac{3r}{4} \left(\frac{Q_{ei} + P_{aux}^i}{\chi_i e B_\theta} \right)$$

The first term on the right hand side has been shown² to lead to Pfeiffer and Waltz (neo-Alcator) scaling. The new second term causes the deterioration of containment with either high density or auxiliary ion heating as observed experimentally.

¹A.A. Ware and J.C. Wiley, Phys. Fluids **24**, 936 (1981).

²A.A. Ware, Comments Plasma Phys. **7**, 199 (1983).

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SELF-CONSISTENT BETA CALCULATION IN RFP*

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ABSTRACT

Beta is found self-consistently in reversed field pinches using collisional transport coefficients of resistivity, thermal conductivity, and viscosity in 3-D MHD numerical computations. The profile dependence of the transport coefficients is included and causes a thermal instability, which tends to peak the current and pressure on axis. On the other hand, the predominantly $m = 1$ tearing modes flatten the profiles. The balance of these effects produces a stationary state with sawteeth. The computed $\beta_0 = 0.5$ is approximately constant over a range of θ and resistivity values, consistent with experiment,¹ and agrees reasonably well with the OHTE¹ value $\beta_0 = 0.3$. The computations make use of the finite beta generalization of reduced MHD equations² derived previously, and shown to agree with standard MHD. The beta value is insensitive to the value of resistivity, because the ion thermal conduction, Ohmic heating, and MHD dynamo effect are proportional to each other. Numerically, a decrease in fluctuation level roughly as $S^{-1/2}$ is seen, as in experiments.¹ Electron thermal conductivity is not included, but sound waves produce a similar smoothing of the pressure along the magnetic field lines.

¹T.N. Carlstrom, B.A.P.S. (1984).

²H.R. Strauss, Phys. Fluids 27, 2580 (1984).

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MAGNETIC COMPRESSION OF ION RINGS IN THE
PRESENCE OF BACKGROUND PLASMA

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Previous studies¹ of the magnetic compression of ion rings have neglected the presence of currents induced in the background plasma or at most treated the background as a very resistive medium. A one-dimensional numerical hybrid code in cylindrical geometry has been developed in which the background cold plasma is treated in the two-fluid approximation and ring ions are treated as particles. This code is employed to study the influence of induced plasma currents on the magnetic compression of ion rings; in particular the effect of the variation of field reversal factor ζ , and ion energy with magnetic field compression. Initial results will be presented.

1. See for example, review by J.M. Finn and R.N. Sudan, Nucl. Fusion, 22, 1443 (1982).

SHERWOOD THEORY MEETING 1985

Madison, Wisconsin

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**Symmetry Breaking in the Noncanonical Hamiltonian
Formalism for Fluids and Plasmas****S. Eliezer[†] and P.J. Morrison[‡]*

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When the Poisson bracket is noncanonical, a symmetry of the Hamiltonian (H) does not always result in a symmetry for the dynamical equations. In this context the Casimir invariants (C) are considered as symmetry breaking terms in the 'effective potential' $I(I = H + C)$. Moreover, the concept of spontaneous symmetry breaking is introduced in analogy with Goldstone's theorem in relativistic field theory. The equilibrium states of the fluid or plasma system correspond to the "vacuum"; i.e. the lowest eigenstate in the quantum system. Spontaneous symmetry breaking yields an equilibrium of smaller symmetry than that of the effective potential I . This phenomenon is related to neutral stability; i.e. the existence of zero eigenvalues for the second variation of the effective potential.

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Monte Carlo Estimation of Confinement in a Tokamak with Ripple^{*}

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Toroidal rippling of the magnetic surfaces in a tokamak, due to the discreteness of field coils, causes diffusion of banana orbits. A unified treatment of the transport coefficients in various regimes can be given from a 2D map representation. The iteration time interval of the mapping is the bounce time of trapped particles. One is then left with the problem of estimating the global transport induced by these coefficients, in particular average particle and energy confinement times. In some situations sensitivity to even small deviations from equilibrium does not permit averaging over a Maxwellian for these estimates. Radial dependencies are another complication. A Monte Carlo analysis is presented which efficiently gives a measure of confinement even in these cases.

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WKB Theory Using Gaussian Wave Packets
and
Exponential Instability in Wave Systems^(a)

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For virtually any wave equation, including integral equations, Gaussian wave packets form a useful means for studying wave evolution in the WKB limit. In this approximation, Gaussian initial conditions remain Gaussian in the course of time, although the parameters describing the wave packet change. The average values $\langle \vec{x} \rangle$ and $\langle \vec{k} \rangle$ evolve according to the Ehrenfest relations along the ray trajectory in phase space. The overall phase of the wave packet as a function of time is the integral of the symmetrized symplectic form $\frac{1}{2}(\vec{k} \cdot d\vec{x} - \vec{x} \cdot d\vec{k})$ along the ray trajectory. The shape and spreading of the wave packet, in both $\vec{x}$ - and $\vec{k}$ -space, are determined by the symplectic matrix $S(t)$ which describes the evolution of nearby ray trajectories. This symplectic matrix is directly related to the Liapunov exponents of classical Hamiltonian systems, which, when positive, indicate exponential divergence of nearby orbits and the presence of stochasticity. Thus wave packets imitate the behavior of classical nearby orbits. Gaussian wave packets do not produce caustics, and can be used in any number of dimensions.

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HYPERBOLIC ISLANDS FILL STOCHASTIC PHASE SPACE

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It is well known that the onset of stochasticity can be roughly predicted by the overlap of islands method where the island sizes are determined by ignoring all resonances but one. Here we precisely define the size of an island as the area enclosed between the stable and unstable manifolds of the unstable periodic orbit. Since, in general, these manifolds transversely intersect, the island boundary contains a turnstile¹ which determines the flux of orbits entering and leaving the island. With this definition, islands never overlap. In fact the island area reaches a maximum when its residue is of order one and decreases as $R^{-\alpha}$ for large R . Since the central elliptic fixed point becomes hyperbolic for $R > 1$, we refer to such islands as hyperbolic. We show that all the area in a region of phase space with no KAM surfaces is filled by islands. This is remarkable, since there are an uncountable infinity of quasiperiodic orbits, the cantori, in such regions as well.

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1. R.S. MacKay, J.D. Meiss, I.C. Percival, *PHYSICA* 13D (1984)55.

SHERWOOD THEORY MEETING 1985

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Particle Simulations of Current Driven Drift Waves

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Current driven drift waves can play a role in determining both the energy confinement time and the dynamo sustainment of RFP's.¹ We have simulated this instability in slab geometry using a 2-1/2D guiding center electrons, full dynamic ions, bounded, electrostatic particle code. Typical parameters are $M_i/m_e = 100$, $T_e/T_i = 1$, $\omega_{ce}/\omega_{pe} = 5$, $\kappa \equiv L_n^{-1} = 0.07$. We have chosen to maintain the current throughout the length of the runs.

Shearless runs, for an angle $\theta = \tan^{-1}(B_y/B_z) = 1^\circ$, yield growth rates in good agreement with linear theory for a wide range of v_d/c_s values. Saturation occurs by global flattening of the density profile accompanied by large global electron parallel heating. Saturation values of $e\phi/T$ are in rough agreement with the mixing length estimate $e\phi/T \sim (k_\perp L_n)^{-1}$. Sheared runs with $L_s/L_n = 14$ also yield growth rates in good agreement with linear theory for many values of v_d/c_s including stability for $v_d/c_s < 3$. Local flattening of the electron density over the mode width and large local parallel electron heating saturate the unstable modes. Saturation values of $e\phi/T$ do not agree with the mixing length estimate, $e\phi/T \sim \kappa\lambda$, where λ is the mode width. Rather, $e\phi/T$ is linearly proportional to v_d/c_s and inversely proportional to $k_\perp^2$. Three dimensional (multiple helicity) extensions of this work are currently being pursued.

¹N.T. Gladd, N.A. Krall, R.W. Moses and A.R. Jacobson, paper IAEA-CN-44, Tenth International Conference on Plasma Physics and Controlled Thermonuclear Research, London, U.K., September 1984.

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Simulations of the Effect of ICRF Waves on the Interchange Instability*

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Recent results from the Phaedrus experiment at Wisconsin suggest that stabilization of the interchange mode in mirror plasma may be possible using RF waves excited externally in the vicinity of the ion-cyclotron frequency.¹ Two simulation codes have been developed for the purpose of studying the effect of ICRF waves on the linear growth rate of the interchange instability. Both codes model essentially the same system. The simulation plane is oriented perpendicular to the background magnetic field. An external gravitational field is fixed antiparallel to the density gradients initially present in the system. Full dynamics of the ions are followed while the electrons are represented as a cold $\mathbf{E} \times \mathbf{B}$ fluid. The plasma is assumed quasineutral and the Darwin approximation is made. In the original code, no significant stabilization is observed for long interchange wavelengths ($kL_n \leq 1$) and large RF fields ($e^2 \nabla |E|^2 / 4m_i^2 \omega^2 g \approx O(1)$). The parameters required for tests of the effects on short wavelength modes ($kL_n \gg 1$) excite numerical instabilities which appear related to an insufficiently accurate representation of the Lorentz force. A new code employing a different algorithm is being developed to bypass this problem. Supporting theory will also be presented.

*Work supported by DOE Contract No. DE-AT03-76ET53064. Computations facilities provided by the National Magnetic Fusion Energy Computer Center.

¹J. R. Ferron, N. Hershkowitz, R. A. Breun, S. N. Golovato, and R. Goulding. Phys. Rev. Lett. **51**, 1955 (1983).

HEATING IN IGNITING PLASMAS^{*}

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Several interesting features that could strongly affect ignition have been observed in the time dependent 1D transport simulation of high current toroidal ignition experiments. These features emphasize the difference in basic physics between sub-igniting and igniting plasmas. The most basic difference is the appearance of a nonconstant toroidal electric field with an elevated edge voltage and depressed central values, with a total Ohmic heating that is less than predicted from the edge value. Such a field develops in cases of strong heating, when $(3/2)(\partial/\partial t)(nT_e)$ becomes significant in the electron energy balance equation, and occurs despite the existence or nonexistence of central sawtooth oscillations or the assumption of classical or neoclassical electrical resistivity, as long as strong heating, which is a necessary condition for attaining ignition in most high field designs. The Ohmic power deposition shifts away from the magnetic axis, favorable for maintaining relatively large Ohmic heating when central temperatures are large enough for significant fusion heating.

A comparison of designs proposed for a compact ignition experiment illustrates the expected relationship between the heating and radiation losses, the particle density, and the ratio B_T/R . Smaller B_T/R designs are able to achieve substantial fusion heating with Ohmic heating alone over a significantly narrower range of density and require a longer heating interval, under the same set of assumptions.

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Ballooning Instability in a Helic

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A field-line-following ballooning mode code is used to study the MHD stability of a Helic configuration. The ballooning equation coefficients are computed for a given field line, and the marginally stable solution determines the critical pressure gradient. The removal of a symmetry constraint used in former work¹ shows that mode localization can occur away from symmetry points at smaller pressure gradients than the symmetric modes previously found. A stability profile study will be presented.

¹H.L. Berk, M.N. Rosenbluth and J.L. Shohet, Phys. Fluids 26, 2616 (1983).

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CONFIGURATION STUDIES FOR THE TJ-II DEVICE*

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Configuration scans and design calculations for the TJ-II device are presented. TJ-II is a collaborative experiment which is to be built in Madrid, Spain. The physical constraints for TJ-II are a major radius of 1.5 m and a 1T magnetic field. A wide range of potential configurations have been investigated. The most promising configuration is the Flexible Helicac [1], which is a helicac [2] with an $\ell = 1$ winding added to the central conductor structure. This additional $\ell = 1$ winding permits the independent variation of α and shear over a wide range. Other benefits of this winding include a deepening of the magnetic well and a reduction of the total current on the central conductors. Design calculations including field error studies will be presented for an optimized Flexible Helicac.

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⁺ Junta de Energia Nuclear, Madrid, Spain.

- [1] J. H. Harris et al., "A Flexible Helicac Configuration," ORNL/TM-9504.
- [2] A. H. Boozer et al., Plasma Phys. and Contr. Nucl. Fus. Res., Vol. 3, IAEA, Vienna (1983) 129.

THE EVOLUTION OF A SPHEROMAK FOR DIFFERENT RESISTIVITY PROFILES*

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We consider a zero- β spheromak contained in a rectangular region having perfectly conducting boundaries to be in its minimum energy state, and we determine its evolution away from this state. Since this initial state is a stable equilibrium, the spheromak would not evolve if all transport coefficients were zero. However, due to nonzero resistivity the spheromak evolves through a sequence of quasi-equilibria in which the plasma inertia is small. At some point in this evolution it may diffuse to an unstable equilibrium, at which time it would relax on an inertial time scale to a different, stable equilibrium. We have previously chosen the resistivity profile $\eta = \eta_0(1-10\psi/11)$, and presented the evolution during the diffusion phase. By checking the equilibria with a 2D linear stability code we found that the spheromak did indeed diffuse to an equilibrium in which the $n = 2$ mode was unstable and the growth time was less than the diffusion time.

In this report we present results for several other resistivity profiles. The plasma profiles are calculated as a function of time by the 1-1/2D transport code MINERVA, and the stability of the profiles is evaluated with a zero beta ideal stability code.

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NONLINEAR STABILITY OF DRIFT-TEARMING MODES

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The stabilization of drift-tearing modes by thermal gradient effects is scrutinized in light of nonlinear physics arising from the effect of the mode on the equilibrium density and temperature profiles. It is shown that linearly growing drift-tearing modes are rendered stable at a very small island width by quasilinear generation of small-scale ripples in these profiles. However, both linearly and quasilinearly stabilized modes grow to large amplitude if the initial island width is larger than the linear tearing layer, because the parallel temperature gradient is eliminated by electron thermal conduction when the islands are this large. Numerical results are presented in support of this argument, as is an analytical calculation which treats the problem as a set of magnetic differential equations. The importance of nonlinear considerations in predictions of stability is thus demonstrated.

*Work supported by DOE.

ASYMPTOTIC THEORY OF FLUIDS WAVES IN RELATIVISTIC PLASMAS^{*}

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A fluid derivation of waves in homogeneous nonmagnetized relativistic plasmas is presented. It is shown that knowledge of the fluid dispersion relations of Langmuir, ion-acoustic and transverse waves relies on the determination of three physical quantities, namely: the polytropic index for the equation of state, a generalized specific heat, and an anisotropy factor related to the traceless part of the stress tensor. Asymptotic analysis is then used, leading to the recognition of four asymptotic regions in the temperature-phase velocity plane, where a simple set of prescriptions can be given for the value of the three quantities mentioned above. In particular, for Langmuir waves, it is found that the correct equation of state is isothermal for temperatures exceeding the electron rest mass.¹

We believe that our method has the advantage of making the physics clearer and the mathematical derivation easier.

¹F. Pegoraro and F. Porcelli, Phys. Fluids 27, 1665 (1984).

INTERPRETATION OF DENSITY PROFILE ANOMALIES
OBSERVED IN PDX IN TERMS OF PLASMA FLOW

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Measurements of density and electron temperature profiles in PDX, in presence of strong NBI, are incompatible with the assumption that the plasma is an axisymmetric, static, isotropic pressure equilibrium.¹ While the electron temperature rises as the heating power increases without a great change in the profile, the density profile becomes strongly skewed with higher density on the outside. This seems to be a "regular feature of strongly-heated plasmas in PDX" and no explanation is offered in ref. 1.

We show that such a feature is always present in any stationary flow equilibrium and could thus be at least a partial explanation of the PDX results. Using our fixed boundary stationary flow equilibrium code CLIO, we have reconstructed self-consistent solutions which fit the published PDX data.¹ In a first step, a static equilibrium has been constructed which reproduces the global parameters β , β_p , q_0 , q_a given in [1] and which has the same pressure profile as in the ohmic phase, only the absolute value being adjusted. A flow is then switched on progressively with the assumptions that the flow is isothermal on a magnetic surface and that it vanishes at the plasma surface. Various combinations of poloidal and toroidal flows have been used which can equally well reproduce the density and temperature profiles. Up to very large flow velocities, the magnetic topology is remarkably rigid, the isobars shifting outwards to give skewed density. A purely toroidal flow, peaked on axis, can be ruled out as the velocity on axis required, to explain the data, is 0.8 the maximum ion thermal velocity, a value which seems definitely too high. But the same good fit can be done with a maximum poloidal flow velocity of only 0.05 the maximum ion thermal velocity with a maximum toroidal flow velocity of 0.2 for a toroidal flow profile of opposite directions inside and outside the torus. The data are also fitted with a poloidal flow of 0.04 and with 0.30 for a toroidal flow velocity mainly on the outside of the torus. Note that in these two examples, the maximum of the toroidal rotation velocity is between the axis and the surface. Such small values cannot be excluded a priori from the experimental information. One would need to consider the role of a high momentum tail due to the beam heating on the coupling between impurity ions used to measure the velocity and this tail may contain a large fraction of the momentum flow.

STUDIES OF A LOW FREQUENCY OSCILLATING FIELD CURRENT DRIVE*

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An extension of previous work^{1,2} on the steady-state current drive scheme based on applying properly phased ac modulating voltages to the reversed-field pinch (RFP) windings is reported. One starts with the basic premise that the field profiles relax to a form $B_\theta = \Phi f_\theta(\theta, r/a)$ and $B_\phi = \Phi f_\phi(\theta, r/a)$ on a timescale short compared to the ac modulating period. Here Φ is the toroidal flux; ϕ and θ are the toroidal and poloidal angles; a is the first wall radius and θ the usual pinch parameter $B_\theta(a)/\langle B_\phi \rangle$ in the cylindrical approximation. The field reversal parameter is then given by $F(\theta) = \Phi f_\phi(\theta, 1)/f_\theta(\theta, 1)$. The analytic study proceeds using the small signal approximation applied to the energy balance equation (Poynting Theorem). Approximate expressions are found for the dc component of toroidal current as a function of $\delta\Phi/\Phi$ and $\delta V_\phi/V_\phi$ which compare quite well with previous numerical calculations using the full nonlinear differential equation.¹ The analytic study predicted that current drive can be obtained even if $F(\theta)$ is a constant. This result which may be relevant to tokamaks is also further confirmed by the numerical solutions. Predictions for the upcoming current drive tests scheduled for the Los Alamos ZT-40M as well as the proposed new ZT-H RFP will be reported.

1. Kurt F. Schoenberg, Robert F. Gribble, and Don A. Baker, Jour. Applied Physics 2519 (1984).
2. M. K. Bevir and J. W. Gray, Proceedings of the Reversed-Field Pinch Theory Workshop, Los Alamos report No. LA-8944-C, 196 (1981).

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QUADRATIC FORM APPROACH TO COLLISIONLESS
INTERNAL KINK MODES IN FINITE-LARMOR-RADIUS REGIMES*

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We present an investigation of internal kink modes in high temperature plasmas, whereby the relevant dynamics within the mode resonant layer is described by the collisionless kinetic equations. We consider realistic situations in which the electron and ion temperatures are comparable, and the scale lengths for density and temperature gradients are comparable too. In addition the ion gyroradius is allowed to be of the order of the characteristic layer width over which the perturbed fields vary. Under these conditions the perturbed electromagnetic potentials obey a set of integro-differential equations¹, that represent a solution of the Vlasov-Maxwell equations valid to all orders in the ion gyroradius. From this a quadratic form has been derived, which is here used to obtain approximate dispersion relations for internal kink modes in finite-temperature-gradient, finite-Larmor-radius regimes. This approach shows that, for values of the ion gyroradius smaller than the ideal MHD mode width, the relevant dispersion relation is very well approximated by the standard small-Larmor-radius relation $-\omega(\omega - \omega_{*i}^p) = \gamma_{\text{MHD}}^2$. Thus the mode is stabilized at sufficiently high beta by the finite ion diamagnetic drift frequency. Deviations from this simple dispersion relation are observed for larger values of the ion Larmor radius, and as the latter increases the mode becomes more unstable. The electron temperature gradient is shown to have a stabilizing effect, whereas the ion temperature gradient is destabilizing. Closed analytic dispersion relations are derived in the limits of low and high betas.

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

¹T.M. Antonsen Jr. and B. Coppi, Phys. Lett. 81A, 335 (1981).

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Universal Drift Wave Stability*

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Drift wave turbulence is studied using a three-dimensional electrostatic particle simulation code in slab geometry with an x -space exponential density gradient, where guiding center electrons and full ion dynamics are utilized. The simulation includes multi-rational surface drift waves which, due to a judicious choice of parameters, insure that the resonance overlap condition is well satisfied. The resulting stochastic electrons are clearly seen in the simulation, and the associated test particle diffusion coefficient is obtained.

Previous analytic analyses of the drift wave problem that incorporates the stochastic electron response have indicated an instability.^{1,2} Using a shooting code solution of the drift wave eigenmode equation in the stochastic regime, a simulation study was set up to include unstable modes. However, the initial simulation results have indicated that all modes are stable, even though all the criteria necessary for the analytic instability analysis are satisfied.

The present drift wave simulation study, which is the body of this presentation, is designed using the shooting code analysis so that all modes (including the fundamental $m = 1$ mode) are unstable. Ion heating results are also presented.

¹S.P. Hirshman and K. Molvig, Phys. Rev. Lett. **42**, 648 (1979).

²C.O. Beasley, K. Molvig, and W.I. van Rij, Phys. Fluids **26**, 678 (1983).

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CALCULATION OF THE ELECTRON CONFINEMENT TIME IN
STELLARATORS AT REACTOR COLLISION FREQUENCIES

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A Monte Carlo code called BETAMC has been developed to couple the neoclassical transport theory of Boozer and Kuo-Petravic to the three-dimensional equilibrium and stability code BETA. The Fokker-Planck drift kinetic equation is solved by a method of split time. Ion and electron confinement times τ_i and τ_e are estimated from the exponential rate of decay of the expected value of an appropriately selected test function. Careful choice of the test function and of initial data leads to good estimates of τ_e as well as τ_i . It is found that the plots of τ_e and τ_i intersect at collision frequencies in the reactor range for configurations like the Heliotron E and the ATF-1. In such cases the effect of an ambipolar electric field becomes negligible. The computer codes are being used to search for stellarator configurations with good confinement properties at reactor collision frequencies as well as satisfactory beta values.

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Implicit Electromagnetic Particle Simulation Code*

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Strongly magnetized fusion plasmas are simulated using an implicit electromagnetic particle code.¹ The simulation is a two-dimensional Cartesian geometry bounded in one direction and periodic in the other. The decentered leapfrog equations of motion² for the electrons follow the $\vec{E} \times \vec{B}$ motion of their guidings center using time steps for which $\Omega_e \Delta t \gg 1$. Ion motion is simulated by either solving the full dynamics for $\Omega_i \Delta t \ll 1$ or following the guiding center approximation when $\Omega_i \Delta t \gg 1$. The solution technique of the implicit field equation divides the operator in a vacuum response and a plasma response. A convenient iteration is obtained by superimposing the adjustments obtained when both parts are separately inverted.

This algorithm has been applied before³ to the simulation of collisionless tearing modes showing good agreement with calculations done using other methods. Test runs for a homogeneous plasma in thermal equilibrium with a constant external magnetic field are presented for regimes in which $\Omega_i \Delta t \ll 1$ or $\Omega_i \Delta t \gg 1$. Several theoretically predicted modes are shown to be present in the simulation results.

¹T. Kamimura, T. Tajima, J-N. Leboeuf, and D.C. Barnes, Bull. Am. Phys. Soc. **27**, 1035 (1982).

²A.Y. Aydemir, D.C. Barnes, and T. Kamimura, Sherwood Theory Conference, Santa Fe, New Mexico (1982).

³E. Montalvo, E. Zaidman, T. Tajima, and D.C. Barnes, Bull. Am. Phys. Soc. **29**, 1295 (1984).

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SIMULATION STUDY OF ELECTRON BERNSTEIN WAVES IN BOUNDED PLASMA*

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The normal modes of a magnetized bounded plasma have been studied. Both body waves and surface waves are observed. Simulation results indicate the existence of electron waves in the frequency range between the first two cyclotron harmonics, which fluid theory does not predict. According to our hypothesis, these waves are Bernstein-like surface waves which do not appear to have been previously described (Bernstein waves with complex $\underline{k}$). A detailed study of these waves has been undertaken. Using a 2-D electrostatic simulation model, we measured the dispersion relations of both body and surface waves with $\vec{B}_0$ parallel to a plasma-vacuum interface and perpendicular to the wave vector, $\underline{k}$. In addition, the waveform (eigenfunction) itself has also been determined using correlation techniques. Our goal is to establish a connection between these new waves and the known Bernstein waves.

* Work supported by USDOE.

Analytic Ballooning Stability Criterion
with finite Shafranov shift in high beta tokamaks

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In high beta tokamaks ($\beta \sim \epsilon$, $\beta_p \sim \frac{1}{\epsilon}$, $\epsilon \equiv \frac{a}{R} \ll 1$), the maximum allowable plasma beta ($\beta \equiv \frac{2p}{B^2}$) is mainly limited by ballooning instabilities. The ballooning stability criterion is computed analytically using a circular flux surface ansatz, in which the Shafranov shift is considered to be comparable to the plasma minor radius. Also intuitive insights into the second stability regime are developed.

TRANSPORT SIMULATIONS OF THE EFFECT OF PROFILE SHAPE ON ALPHA HEATING IN TFTR*

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BALDUR, a one-dimensional transport code¹ is being used to investigate the effect of peaked density and temperature profiles on alpha heating in TFTR. A zero-dimensional calculation shows that for peaked profiles central alpha heating can be significant, creating a "central ignition" region.

The BALDUR simulations specify anomalous electron transport and Hinton-Hazeltine ion neoclassical conduction. The peaked density profile is maintained with a inward pinch balancing outward diffusion. The classical alpha particle orbits at 50kG are confined within 20cm. Sawteeth are included. The role of impurity radiation is small. The simulations included 25MW neutral beam injection and compression of 2.2MA in 30ms with compression ratio of 1.25.

Initial transport simulation studies show that peaked profiles increase alpha production but that heating profiles which are flat or peaked off axis and sawtooth losses can broaden the alpha fusion power profile and prevent the formation of a central ignition region.

*Work supported by US DOE Contract No. DE-AC02-76-CHO-3073

¹C. E. Singer, D. E. Post, D. R. Mikkelsen, M. H. Redi, A. McKenney et al., "BALDUR: A One-dimensional Plasma Transport Code," Princeton Plasma Physics Laboratory Report No. PPPL-2073 (1983)