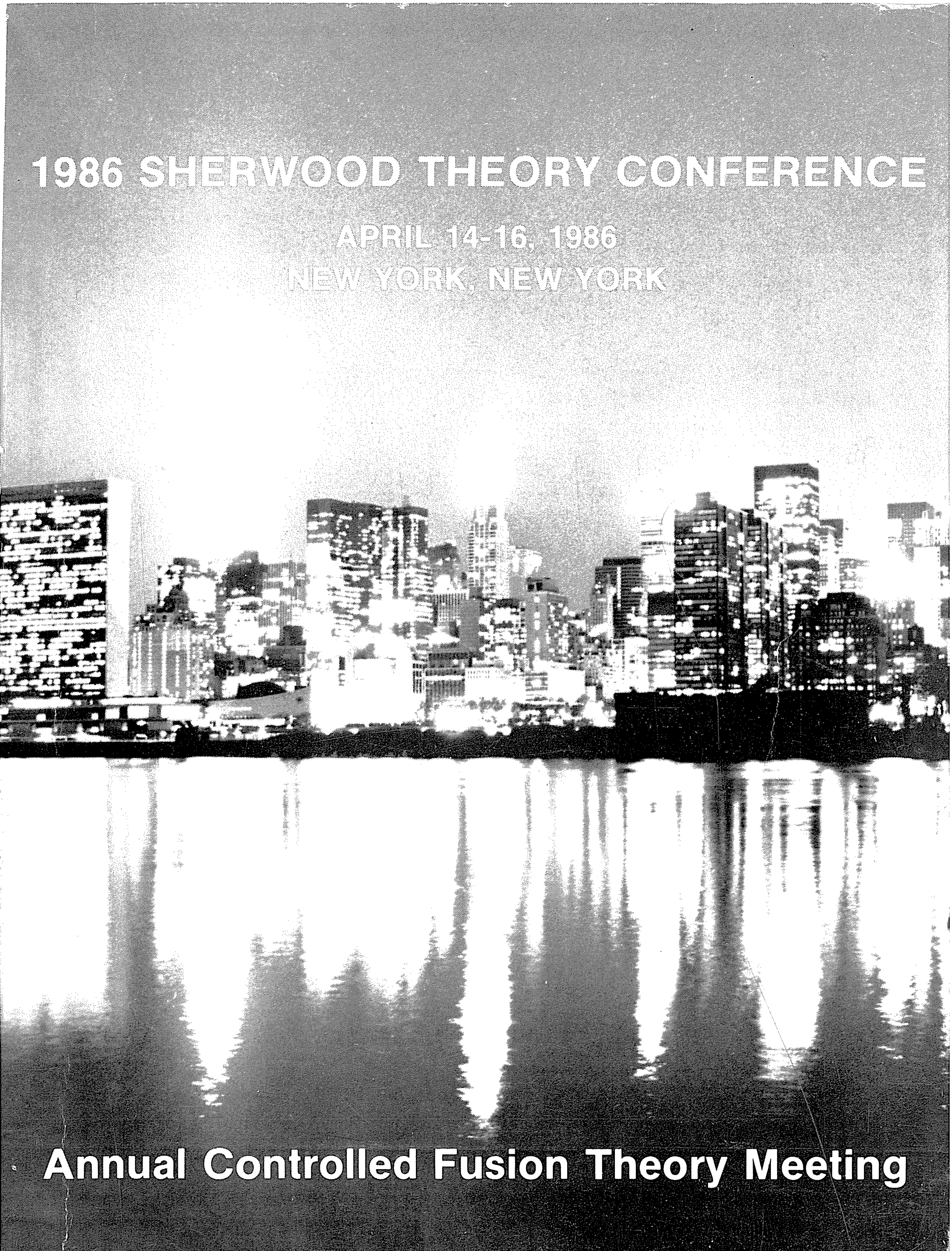
Sherwood '86

1986 SHERWOOD THEORY CONFERENCE

APRIL 14-16, 1986
NEW YORK, NEW YORK



Annual Controlled Fusion Theory Meeting

W. Horton

1986
Sherwood Controlled Fusion Theory Conference

April 14–16, 1986
Penta Hotel, New York, NY

Hosted By

Courant Institute of Mathematical Sciences
New York University
New York, NY

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GENERAL INFORMATION

* 245 papers were submitted, of which 11 were selected for oral presentation.

* The Review papers will be presented in the SkyTop Room, 18th floor, Monday morning beginning at 8:40 am and Tuesday morning beginning at 9:00 am.

* All oral papers will be presented in the SkyTop Room, 18th floor, Monday morning beginning at 9:40 am and Tuesday morning beginning at 10:00 am. Each talk will be 25 minutes in length plus 5 minutes for discussion.

* Poster sessions will be held in the PennTop South Room, 18th floor, Monday afternoon, Tuesday evening, and Wednesday morning.

* Beverages will be served in the PennTop Center Room: coffee and tea during the morning sessions; coffee and ice tea during the afternoon session, and coffee, tea, and beer during the evening session.

* The Conference Registration Desk has information about restaurants, sightseeing and any other information you may require for your convenience.

* Requests for special meetings should be made with Malvina Harris at the Conference Registration Desk.

1986 SHERWOOD THEORY CONFERENCE SCHEDULE
NEW YORK PENTA HOTEL
APRIL 14 - 16, 1986

Registration
April 13, 1986 - 6:00 PM to 10:00 PM
Main Lobby Rear Arcade

April 14 - 16, 1986 - 8:00 AM to 5:00 PM
18th Floor

ORAL AND POSTER SESSION SCHEDULE

All Sessions will be held on the 18th floor
Posters - PennTop Room South
Orals - SkyTop Room

Monday, April 14, 1986

Welcome - 8:30 AM

1A - 8:40 - 9:30 AM (Review Paper)

1B - 9:40 AM - 12:40 PM (Oral Session)

12:40 - 2:00 PM - LUNCH

1C - 2:00 - 4:00 PM (Poster Session)

1D - 4:10 - 6:10 PM (Poster Session)

Tuesday, April 15, 1986

2A - 8:30 - 9:20 AM (Review Paper)

2B - 9:30 AM - 12:30 PM (Oral Session)

12:30 - 6:45 PM - AFTERNOON FREE

2S - 6:45 - 7:35 PM (Special Session)

2C - 7:00 - 9:00 PM (Poster Session)

2D - 9:10 - 11:10 PM (Poster Session)

Wednesday, April 16, 1986

3C - 9:00 - 11:00 AM (Poster Session)

3D - 11:10 - 1:10 PM (Poster Session)

3E - 11:10 - 1:10 PM (Supplemental, Postdeadline Session)

Refreshments - PennTop Center Room

Coffee and Tea - 9:30 AM - Monday, Tuesday, and Wednesday

Coffee and Ice Tea - 2:30 PM - Monday

Coffee, Tea, and Beer - 8:00 PM - Tuesday

1986 SHERWOOD THEORY CONFERENCE
ANNUAL CONTROLLED FUSION THEORY CONFERENCE

New York Penta Hotel
New York, New York
April 14 – 16, 1986

REGISTRATION – Sunday, April 13, 6:00-10:00pm
Main Lobby – Rear Arcade

REGISTRATION – Monday, April 14, 8:00-5:00pm
18th floor

MONDAY MORNING 8:30 – 12:40pm

WELCOME 8:30

1A REVIEW SESSION
8:40am SkyTop Room
Presiding: Dave Ross

1A1. Particle Transport in Tokamaks. A. J. Wootton.

1B ORAL SESSION – Tokamaks
9:40am SkyTop Room
Presiding: Roscoe White

1B1. Compound Sawteeth in Tokamaks. R. E. Denton, J. F. Drake, R. G. Kleva, and D. A. Boyd.
1B2. Beta Limits in Racetrack-shaped Tokamaks. A. D. Turnbull, R. Gruber, S. Nicli, A. Roy, O. Sauter, and F. Troyon.
1B3. Ideal MHD Ballooning Stability in Divertor Tokamak– A Picture of the H-Mode. C. M. Bishop.
1B4. Theory of Ion-Temperature-Gradient-Driven Turbulence and Anomalous Transport in Tokamaks. G. S. Lee and P. H. Diamond.
1B5. Tokamak Transport Code Simulations with Drift Wave Models. R. R. Dominguez and R. E. Waltz.
1B6. Physics and Design Issues for Ignition Experiments. B. Coppi.

LUNCH 12:40 – 2:00

MONDAY AFTERNOON 2:00 – 6:10pm

1C POSTER SESSION
2:00 – 4:00pm PennTop Room South

1C1. Alpha Particle Heating in the FPD Mirror Central Cell. C. K. Choi and K. B. Cravens.

1C2. MHD Current Generation: Elongation Pumping and Transform Control. J. T. Hogan.
1C3. Structure and Dynamics of Coherent Structures in Tokamak Edge Turbulence. T. S. Hahm, P. H. Diamond, and P. W. Terry.
1C4. Comparison of Various Thermal Conduction Models in the Prediction of Density Limits in Tokamaks. J. Q. Dong and P. N. Guzdar.
1C5. MHD Smorgasbord. J. P. Freidberg.
1C6. Practical Generalized Energy Principles for Determining Linear and Nonlinear Stability. P. J. Morrison and M. Kotschenreuther.
1C7. Sawtooth Oscillations and Transport in Compact Ignition Tokamaks. G. Bateman.
1C8. Radial Electron Transport Associated with Fast Wave Current Drive. D. Jovanovic and G. J. Morales.
1C9. Theoretical Studies of Lower Hybrid Current Drive in the Versator II Tokamak. P. T. Bonoli, M. Mayberry, and M. Porkolab.
1C10. Radial Localization of Drift Cone and Ion-Cyclotron Loss Cone Modes. G. R. Burkhart and P. N. Guzdar.
1C11. Nonlinear Model for Drift Wave Turbulence. F. W. Perkins.
1C12. Pastukhov Problem in Toroidal Devices. Y. B. Kim and J. D. Callen.
1C13. Multiple-Wave Calculations of Wave-Driven MHD Equilibria. K. Evans, Jr. and D. A. Ehst.
1C14. ICRF Wave Coupling and Antenna Design with High Beta Tokamak Equilibria. R. S. Elet, G. A. Navratil, C. K. Phillips, and D. Q. Hwang.
1C15. Half-Implicit Guiding Center Electrostatic Particle Codes. J. H. Han and J. N. Leboeuf.
1C16. Transport Simulations of TFTR Ohmic Plasmas. M. H. Redi, W. M. Tang, P. C. Efthimion, A. H. Kritz, D. R. Mikkelsen, C. E. Bush, J. Schivell, and B. C. Stratton.
1C17. Studies of Neoclassical Equilibrium Distribution Functions for Stellarator and Bean-Shaped Tokamak Plasmas. C. O. Beasley, Jr., W. I. Van Rij, E. C. Crume, Jr., S. P. Hirshman, and K. C. Shaing.
1C18. Analysis of Radial Transport and Ohmic Heating of a Confined Plasma. P. Rosenau.
1C19. Sawtooth Oscillation Studies. W. Park and D. A. Monticello.
1C20. Stochastic Motion of a System with Two Degrees of Freedom Induced by Two Perturbing Waves. K. Hizanidis and C. Menyuk.
1C21. Moving Finite Element Simulation of the Fiber-Initiated Dense Z Pinch. A. H. Glasser.
1C22. Modeling of Electron-Cyclotron Heating in Tandem Mirrors. G. R. Smith, W. M. Nevins, D. Ress, and S. Tamor.
1C23. Single Particle Simulation of RF Drift Pumping in Phaedrus-B. J. W. Johnson, R. A. Breun, and J. D. Callen.
1C24. Energy Principle for Toroidal Plasma with Boundary Effect. Y. Kondoh and T. Yamagishi.
1C25. Trapped Electron Effects on Anomalous Ion Heat Transport. Y. K. Pu, R. England, and S. Migliuolo.
1C26. Magnetically Insulated Impact Fusion. D. C. Barnes.
1C27. Sawtooth Oscillations in Finite Aspect Ratio Tokamaks. R. Izzo, D. A. Monticello, W. Stodiek, and R. B. White.
1C28. Current Ramp and Ignition in a High Field Tokamak. R. C. Englade and L. E. Sugiyama.
1C29. Effects of Thermionic Electron Emission on the Sheath. M. J. Embrechts, D. Steiner, and A. Kawano.
1C30. Alpha Particle Driven Compressional Alfven Instability. T. M. Antonsen, Jr., H. L. Berk, and H. V. Wong.
1C31. Fully-Developed Drift Wave Turbulence. R. N. Sudan and M. N. Rosenbluth.
1C32. The Influence of End-Plate Potential Control on MHD Stability and Drift Pumping in Mirror Plasmas. T. B. Kaiser and B. I. Cohen.
1C33. The Anomalous Doppler Instability during Lower-Hybrid Current Drive. S. C. Luckhardt, A. Bers, V. Fuchs, and M. Shoucri.
1C34. Transport in Reversed-Field Pinches due to the Turbulent Electric Field. Y. C. Kwok, A. Bhattacharjee, C. K. Chu, and E. Hameiri.
1C35. Anomalous Thermal Confinement in Auxiliary-Heated Tokamaks. F. Romanelli, W. M. Tang, and R. B. White.
1C36. Enhancement of Radial Transport by Nonlinear Collective processes. D. L. Eggleston, T. M. O'Neil, J. D. Crawford, and J. H. Malmberg.
1C37. Development and Application of a Three-Dimensional Magnetoinductive Particle Code. E. Zaidman and T. Tajima.

1C38. New Solutions for Two-Dimensional MHD Equilibria. E. R. Tracy and H. H. Chen.
1C39. MHD Stability in Elongated Tokamak Discharges. A. M. M. Todd and M. W. Phillips.
1C40. Initial Value Approach to the MHD Field Error Problem. Y. Z. Agim and S. C. Prager.

1D POSTER SESSION

4:10 – 6:10pm PennTop Room South

1D1. Direct Solution for the Power Spectrum of a Chaotic System. P. L. Andrews and R. E. Waltz.
1D2. Analysis of Runaway Confinement Data from the ASDEX Tokamak. O. J. Kwon, P. H. Diamond, T. S. Hahm, and F. Wagner.
1D3. FRC Tilting Stability Results with the Self-Consistent Eigen-function. J. L. Schwarzmeier, D. C. Barnes, and H. R. Lewis.
1D4. Parametric Processes in Ion Cyclotron Heated Plasmas. R. D. Sydora and J. M. Dawson.
1D5. Feasibility of Gyrokinetic Particle Simulation of Tokamaks. W. W. Lee.
1D6. Nonlinear Theory of Energetic Trapped Particle-Induced Resistive Interchange Modes. H. Biglari and L. Chen.
1D7. Simulation of Lower Hybrid Wave Current Ramp-up. W. Shyu.
1D8. Ideal and Resistive MHD-Stable Regime of the Tokamak. C. Z. Cheng, H. P. Furth, and A. H. Boozer.
1D9. Stability Criteria and Relaxed States for Double Adiabatic MHD. G. Sun and J. M. Finn.
1D10. Alpha Particle Effects on Plasma Equilibria. W. Grossmann and R. N. Byrne.
1D11. Turbulent Drift-Wave Dynamics in a Sheared Slab with a Search for Coherent Structures. B. D. Scott, P. H. Diamond, and P. W. Terry.
1D12. High-Speed Pellet Fueling of OHTE/RFP Plasmas: Theory Issues. J. C. DeVeaux and S. E. Walker.
1D13. Calculation of Fourier Coefficients on a Rational Magnetic Surface. X. Llobet, H. L. Berk, T. T. Lee, and K. V. Roberts.
1D14. The Establishment of the Electrostatic Field in a Stellarator. J. L. Shohet and W. N. G. Hitchon.
1D15. On the Velocity-Space Structure of Runaway Electrons. R. A. Cairns, V. Fuchs, C. N. Lashmore-Davies, and M. Shoucri.
1D16. Stationary Resistive Equilibria in Tokamaks. O. Sauter, A. D. Turnbull, A. Roy, R. Gruber, and F. Troyon.
1D17. Current and Beta Limitations in Tokamaks. F. Troyon and A. D. Turnbull.
1D18. Numerical Solutions for a CIT Divertor Model. G. Kuo-Petravic, M. Petravic, and D. Heifetz.
1D19. Electron Cyclotron Whistler Mode Excitation and Application in a Tokamak. H. Hsuan and R. M. Kulsrud.
1D20. MHD Simulation of Columbia HBT for 2nd Stable Regime Equilibria. X-L. Li, A. A. Grossman, and C. K. Chu.
1D21. Nonlinear Reduced MHD Equations with Magnetic Pumping in Toroidal Plasmas. J. F. Drake and A. B. Hassam.
1D22. Equilibria in Ellipsoidal Coordinate System. M. S. Chu.
1D23. Effect of Large-Amplitude Perpendicularly-Propagating RF Waves on the Interchange Instability. N. F. Otani and B. I. Cohen.
1D24. 3D Transport Simulation I: Code and Variations. A. Bayliss, M. Hossain, S. Dinkevich, and H. Grad.
1D25. Calculations of Electron Distributions for Thermal-Barrier Tandem Mirrors. J. J. Stewart, Jr., Y. Matsuda, T. D. Rognlien, and R. H. Cohen.
1D26. Modelling of ECRH-heated Electrons in Tandem-Mirror Thermal Barriers. R. H. Cohen, A. Friedman, and G. D. Porter.
1D27. Fast Wave Coupling to Ion-Bernstein Wave in Tokamak Edge Plasma During ICRF Heating. S. N. Antani and J. E. Scharer.
1D28. Spheromak Tilt Stabilization with Particle Rings. C. Mehanian and R. V. E. Lovelace.
1D29. Confinement Analysis of Compact Ignition Tokamak (CIT). N. A. Uckan and W. A. Houlberg.
1D30. Toroidal Divertor Tokamak. T. Yamagishi, T. Ohkawa, and M. S. Chu.
1D31. Turbuleeent MHD Transport Coefficients: A New Approach. H. Chen and D. Montgomery.
1D32. Enhancing Fusion Reactor Efficiency by Breaking Reaction product Adiabaticity in Advanced Fuel Tandem Mirrors. J. F. Santarius.

1D33. Resistive Ballooning Stability with Highly Energetic Particles. N. Dominguez, J. W. Van Dam, M. N. Rosenbluth, S. C. Guo, J. W. Shen, and S. T. Tsai.
1D34. Trapped Particle Modes in the Presence of Radiofrequency Waves. D. K. Bhadra and S. C. Chiu.
1D35. One-Dimensional Modelling of DC Current Drive by AC Helicity Injection in a Tokamak. P. C. Liewer, R. W. Gould, and P. M. Bellan.
1D36. Simulation Study of Nonlinear Ohm's Law. P. N. Yushmanov and J. N. Leboeuf.
1D37. Effect on Tearing Modes of Different Formulations of the Incompressibility Condition. L. A. Charlton, B. A. Carreras, J. A. Holmes, H. R. Hicks, and V. E. Lynch.
1D38. A Relativistic Fokker-Planck Algorithm for Computing ECRH in Tokamaks. M. R. Franz and G. D. Kerbel.
1D39. 3D Transport Simulation: Applications. M. Hossain, A. Bayliss, M. E. Kress, J. T. Hogan, and H. Grad.
1D40. The Alfven Effect Reconsidered: Effects of Reconnection and High Viscosity on the Spectrum of MHD Fluctuations. W. H. Matthaeus.

TUESDAY MORNING 8:30 – 12:30pm

2A REVIEW SESSION –
8:30am SkyTop Room
Presiding: Leaf Turner

2A1. Lattice Gas Hydrodynamics. B. Hasslacher.

2B ORAL SESSION – Alternative Concepts and Basic Theory
9:30am SkyTop Room
Presiding: Hank Strauss

2B1. Theory and Operation of the m=1 Helicity Source Experiment. G. J. Marklin, B. L. Wright, J. C. Fernandez, T. R. Jarboe, and D. A. Platts.
2B2. Semi-Implicit Magnetohydrodynamic Calculations. D. D. Schnack, D. C. Barnes, Z. Mikic, D. S. Harned, E. J. Caramana, and R. A. Nebel.
2B3. A Fluid Theory of Plasma Currents Induced by Waves. K. C. Shaing and S. P. Hirshman.
2B4. Progress on the Theory of Field-Reversed Configurations and Comparison with Experiments. L. C. Steinhauer.
2B5. Vortex States in Inhomogeneous Rotating Plasma. W. Horton, J. Liu, and J. D. Meiss.
2B6. Some Properties of the MHS Equilibria and Nonexistence of the Isodynamic Stellarator. D. Palumbo.

TUESDAY AFTERNOON FREE

TUESDAY EVENING 6:45 – 11:10pm

2S SPECIAL SESSION –
6:45–7:35pm SkyTop Room
Presiding: Dave Nelson

2C POSTER SESSION
7:00–9:00pm PennTop Room South

2C1. Magnetic Helicity and the Ohm's Law for Mean Magnetic Fields. A. H. Boozer.

2C2. Ion Bernstein Modes in the Presence of a Poloidal Magnetic Field. J. L. Milovich.
2C3. Relativistic 2-D Fokker-Planck Code for Lower-Hybrid Current Drive. M. Shoucri, V. Fuchs, and A. Bers.
2C4. A Model for TFTR Ohmic Discharges. L. E. Sugiyama and J. Martinell.
2C5. Gyroviscous Effects in the Stress Tensor for Tokamak Plasmas in the Plateau Regime. D. J. Sigmar, G. Vahala, and L. Vahala.
2C6. Nonlinear Coupling of Tearing Modes in the Reversed Field Pinch. J. A. Holmes, B. A. Carreras, and V. E. Lynch.
2C7. Parametric Excitation of an Ion Acoustic Wave by an Electron Cyclotron Wave. K. Matsuda.
2C8. Analytical Description of Cold Plasma Surface Alfven Eigenmodes in Slab Geometry. W. Q. Li, D. W. Ross, and S. M. Mahajan.
2C9. Nonlocal Lower-hybrid-drift Waves and One-Dimensional Transport Modeling in a Field Reversed Configuration. S. Hamasaki, N. T. Gladd, and N. A. Krall.
2C10. Numerical Simulation of Transport in Field Reversed Configuration. D. E. Shumaker.
2C11. Momentum and Energy Confinement in Tokamaks with Neutral Injection. N. Mattor, P. H. Diamond, and G. S. Lee.
2C12. Another FRC Equilibrium Code. R. B. Webster and J. L. Schwarzmeier.
2C13. Stability of m=0 Islands in the RFP. R. A. Nebel, G. J. Marklin, and D. D. Schnack.
2C14. Effect of Flow Shear on Nonlinear Tearing Modes. A. B. Hassam and T. M. Antonsen, Jr..
2C15. Parametric Interaction of ICRF with low Frequency Turbulence in Tokamaks. S. C. Chiu, V. S. Chan, and D. K. Bhadra.
2C16. Effect of Toroidal Flow on Ballooning Modes. C. Paranicas and A. Bhattacharjee.
2C17. Quasilinear and Steady Electric Field Effects on Electron Cyclotron Heating. R. W. Harvey, M. G. McCoy, G. D. Kerbel, R. T. Snider, and R. Prater.
2C18. A Fully Implicit Field Solver for 3D Particle Simulation Codes. D. V. Anderson, E. J. Horowitz, A. E. Koniges, and D. E. Shumaker.
2C19. Normal Mode Simulation as a Test for 3D Particle-in-Cell Code. E. J. Horowitz and D. E. Shumaker.
2C20. Turbulence Models in Plasma Physics. A. E. Koniges and C. E. Leith.
2C21. Collisional Drift-Wave Turbulence with n(e) Effect. B. G. Hong, W. Horton, and D.-I. Choi.
2C22. ICRF Fundamental Minority Heating in Inhomogeneous Plasmas. H. Romero and J. E. Scharer.
2C23. Fusion Sustained Current in the Field-Reversed Configuration. T. Tajima, H. L. Berk, M. Lebrun, and H. Momota.
2C24. On the Presence of the Lower Hybrid Drift Instability in the Field Reversed Configuration. A. G. Sgro and N. T. Gladd.
2C25. Role of Surface Effects in RF Stabilization of Axially Symmetric Systems. C. Litwin.
2C26. Trapping/detrapping Orbits in Nonsymmetric Toroidal Magnetic Fields. J. R. Cary.
2C27. Ion Temperature Gradient Driven Drift Mode in a Reversed Field Pinch. N. T. Gladd.
2C28. Stabilization of the m=1 Interchange Mode by Applied ICRF. J. R. Myra, D. A. D'Ippolito, and G. L. Francis.
2C29. Pressure Surface Distortion by ICRF and Magnetic Error Fields. D. A. D'Ippolito and J. R. Myra.
2C30. Comparison of Plasma Formation Methods in the Coaxial Slow Source. K. D. Hahn and D. C. Barnes.
2C31. Alternating Dimension Formulation of Neoclassical Plasma Transport in Axisymmetric Toroidal Systems. P. N. Hu.
2C32. Transport During Transient Plasma Perturbations in TEXT. D. W. Ross, W. H. Miner, and J. C. Wiley.
2C33. High-q Simulations of Tearing Modes. R. E. Waltz and J. S. Kim.
2C34. Plasma Potentials in the Divertor Region of Stellarators. G. A. Emmert and M. Hussein.
2C35. The Effect of Toroidal field on the Stability of Heliotron E. L. Garcia, B. A. Carreras, and V. E. Lynch.
2C36. Consistency of Nonlinear Selfdamping. C. G. Schultz and R. N. Sudan.
2C37. Stability of an Axisymmetric Mirror with an Energetic Ion Component. J. F. Krall, C. E. Seyler, and R. N. Sudan.
2C38. Poloidal Electric Field Generated by Electron Cyclotron Heating in a Collisional Tokamak Plasma. V. S. Chan and S. K. Wong.
2C39. Nonlocal Analysis of the Budden-Tunneling Problem. A. Fruchtman, H. Weitzner, and D. B. Batchelor.

2C40. A Partially Elliptic 3D Model of RFP Dynamics. E. J. Caramana.

2D POSTER SESSION
9:10–11:10pm PennTop Room South

2D1. Magnetic Divertor Stabilized Confinement Devices. J. Kesner, M. J. Gerver, B. Lane, Y. T. Lau, and R. S. Post.
2D2. Modeling and Transport Simulations of F-theta Pumping in the RFP. R. A. Scardovelli, R. A. Nebel, K. A. Werley, and G. H. Miley.
2D3. Lower-Hybrid Sloshing-Ion Instability in TMX-U. L. S. Hall.
2D4. Nonlinear Fluid Equations for Toroidal Resistive Modes in the Plateau Collisionality Regime. M. Kotschenreuther and A. Y. Aydemir.
2D5. A Passive or Very Low Frequency Drift Pumping Scheme. J. A. Byers.
2D6. Transport Simulation Results from the FRC Transport Code for the IPSG Representative Discharges. W. H. Miner, D. W. Ross, and J. C. Wiley.
2D7. Ballooning Stability of Tokamaks with an Isotropic Alpha Distribution and Realistic Equilibrium Models. D. A. Spong, D. J. Sigmar, J. J. Ramos, W. A. Cooper, and E. E. Hastings.
2D8. Alfven Ion-Cyclotron Instability in Mirrors with Fanning Geometry. K. T. Tsang and G. R. Smith.
2D9. The Alpha Particle Induced Fishbone Mode. R. B. White, L. Chen, M. S. Chance, and W. M. Tang.
2D10. Ideal MHD Stability of TFTR. J. Manickam and N. Pomphrey.
2D11. Testing Tokamak Transport Models by Predictive Simulations. C. E. Singer, L. P. Ku, and G. Bateman.
2D12. Turbulent Relaxation to a Force-Free Field -Reversed State. J. P. Dahlburg, D. Montgomery, G. D. Doolen, and L. Turner.
2D13. The Minimum Scaling Law of Tokamak. S. M. Mahajan and Y. Z. Zhang.
2D14. Dynamos, Disruptions, and F-theta Pumping. H. R. Strauss and D. S. Harned.
2D15. Scrape-off Layer Fluctuations and Transport including Limiter and Radiation Effects. D. R. Thayer, P. H. Diamond, and A. J. Wootton.
2D16. Shape Control of Elongated Tokamaks. S. C. Jardin, R. Izzo, N. Pomphrey, and W. Schneider.
2D17. Beta-Limit, Current-Disruption, and Profile Consistency. J. K. Lee, L. Lao, J. M. Greene, G. Jahns, A. Kellman, N. Ohyabu, R. Stambaugh, and E. Strait.
2D18. Vortex Solutions in Driftwave Turbulence. K. H. Spatschek and E. W. Laedke.
2D19. Covariant Variational Approach to Electromagnetic Wave Propagation Maslov Transforms, Polarization Transport, and Angular Momentum. Y. Hui, A. N. Kaufman, and H. Ye.
2D20. The Mode Conversion- Tunneling Equation in the Paraxial Propagation Limit. C. K. Phillips, P. L. Colestock, D. Q. Hwang, and D. G. Swanson.
2D21. Destabilization of Alfven-Resonant Modes by Resistivity and Diamagnetic Drifts. A. Y. Aydemir, R. D. Hazeltine, J. D. Meiss, and M. Kotschenreuther.
2D22. Interaction of Electrostatic Drift Holes and Normal Modes in a Plasma. P. W. Terry, P. H. Diamond, and T. S. Hahm.
2D23. MHD Equilibrium and Stability Code with General Topology. O. Betancourt and P. Garabedian.
2D24. 3D Alternating Dimension Energy Dissipation Simulation in a Tokamak. M. E. Kress and H. Grad.
2D25. Nonlinear Behavior of Electrostatic Plasma Waves. Y.-P. Pao.
2D26. Transport in a Toroidally Rotating Tokamak. I. B. Bernstein, P. J. Catto, and M. Tessarotto.
2D27. Gas Breakdown by Second Harmonic ECH. M. D. Carter, D. B. Batchelor, and A. C. England.
2D28. Analytic Calculation of Neutral Penetration into a Plasma. S. P. Auerbach and T. B. Kaiser.
2D29. Optimized Formation of Relativistic-Electron Plasmas in Tokamaks Using Multiple-Frequency Electron Cyclotron Heating. G. E. Guest, C. S. Chang, R. A. Dandl, R. L. Miller, and B. H. Quon.
2D30. Electron Diffusion in Tokamaks due to Electromagnetic Fluctuation. D.-I. Choi and W. Horton.
2D31. Excitation of Ion Bernstein Waves in a Nonuniform Plasma. R. D. Ferraro and B. D. Fried.
2D32. Neoclassical Transport in Bean-shaped Tokamak Plasmas. E. C. Crume, Jr., C. O. Beasley, Jr., S. P. Hirshman, K. C. Shaing, and W. I. Van Rij.
2D33. Ion and Electron Convective Losses due to Poloidal Electrostatic Fields in Toroidal Devices. J. S. Tolliver and C. L. Hedrick.

2D34. Computer Simulations of Ion-Temperature-Gradient-Driven Turbulence. J. N. Leboeuf, R. D. Sydora, G. S. Lee, and P. H. Diamond.
2D35. Nonlocal Resistivity and the Kinetic Dynamo in the Reversed Field Pinch. R. W. Moses.
2D36. MHD Model with the Hall Term. F. Kazeminejad, J. N. Leboeuf, R. D. Sydora, J. M. Dawson, and F. Brunel.
2D37. A 3D MHD Equilibrium Code that does not Assume the Existence of Good Flux Surfaces. A. H. Reiman and H. S. Greenside.
2D38. Enhancement of the Parallel Wavenumbers on the Mode-Converted Ion-Bernstein ICRF Waves. A. Ram and A. Bers.
2D39. Taking Advantage of Parallelism on the Cray Multiprocessors - A Question and Answer Session. L.L.N.L. Computational P.

WEDNESDAY MORNING 9:00 - 1:10pm

3C POSTER SESSION
9:00-11:00am PennTop Room South

3C1. Effect of Collisions on the Trapped Particle Modes in the Columbia Linear Machine. O. Mathey and A. K. Sen.
3C2. Temperature Anisotropy Driven Low Frequency Instabilities in Homogeneous Plasmas. S. Migliuolo.
3C3. Inhomogenity and the Nonlocal Character of Turbulent Plasma Transport. R. A. Smith and J. A. Krommes.
3C4. Radial Diffusion of Plasma Current due to Secondary Emission of Electrostatic Waves by Tail Electrons. V. K. Decyk, G. J. Morales, J. M. Dawson, and H. Abe.
3C5. Differential Renormalization Group Equation for Alfven Wave Turbulence. Y. Zhou and G. Vahala.
3C6. Positron Production by Fusion Devices and Potential Applications. J. M. Dawson and P. L. Pritchett.
3C7. Ponderomotive Stabilization of Mirrors. P. Similon.
3C8. Hybrid Simulation of Quadrupole Stabilization on the FRX-C/T Field-Reversed Configuration Experiment. D. S. Harned and D. J. Rej.
3C9. Computational Studies of Accelerated Compact Toroids. J. L. Eddleman, J. H. Hammer, and C. W. Hartman.
3C10. A New Mode of Electron Surface Wave on a Vacuum-Plasma Interface. D. Sultana, V. K. Decyk, and J. M. Dawson.
3C11. Resistive Evolution of Helical Magnetic Islands. G. Miller, A. White, and V. Faber.
3C12. The High-Frequency Conductivity in a Plasma with Parallel Magnetic Field Gradients. P. L. Colestock, R. J. Kashuba, and G. D. Kerbel.
3C13. Orbit Integral Propagators. G. D. Kerbel.
3C14. Vertical Stability of Shaped Tokamaks. J. J. Ramos.
3C15. A Model for Minority Absorption in Ion Cyclotron Heating. G. L. Francis, A. Bers, and V. Fuchs.
3C16. Equilibrium of Axisymetric Plasmas with Flow. Y. Baransky and C. K. Chu.
3C17. Mode Coupling Between the Fast and Slow Branches of the Extraordinary Mode at the Fundamental Ion Cyclotron Resonance. K. Imre and H. Weitzner.
3C18. Global Waves in Hot and Cold Plasmas. E. F. Jaeger, H. Weitzner, and D. B. Batchelor.
3C19. Neoclassical MHD Equations, Instabilities and Transport in tokamaks. J. D. Callen, W. X. Qu, and K. C. Shaing.
3C20. Sawtooth Crash Time. R. G. Kleva, J. F. Drake, and R. E. Denton.
3C21. Collisionless Electron Temperature Gradient Instability. Y. C. Lee, J. Q. Dong, P. N. Guzdar, and C. S. Liu.
3C22. ECH Stochastic Heating in Stellarators. L. Goes, J. Treffert, and J. L. Shohet.
3C23. Numerical Simulation of Ion Cyclotron Wave Propagation in Mirror Confined Plasmas. M. W. Phillips.
3C24. Resonant Transport in a Rippled Tokamak. J. Albert and A. H. Boozer.
3C25. Electromagnetic Toroidal Quasilinear Transport Coefficients for Trapped-Electron and Kinetic MHD-Ballooning Modes. G. Rewoldt and W. M. Tang.
3C26. Numerical Calculation of Mercier Stability Limits in Spheromaks. R. M. Mayo and G. J. Marklin.

3C27. Alven Waves in a Shear Magnetic Field. S. Yoshikawa.
3C28. Ion Bootstrap Current and the H-Mode. F. L. Hinton.
3C29. Ion Viscosity Stabilization of Resistive Internal Kinks. F. Porcelli and S. Migliuolo.
3C30. Runaway Electron Distributions and their Stability with Respect to the Anomalous Doppler Resonance. V. Fuchs, M. Shoucri, J. Teichmann, and A. Bers.
3C31. The Calculation of Lyapunov Spectra. J. M. Greene and J. S. Kim.
3C32. Plasma Presheath in a Collisional Plasma. J. T. Scheuer and G. A. Emmert.
3C33. Electron Cyclotron Heating in ATF. R. C. Goldfinger and D. B. Batchelor.
3C34. Stability of Cylindrical Plasma in Bessel Function Model with Vacuum Region. C. G. Gimblett, T. Yamagishi, and M. S. Chu.
3C35. Ion Trapping Rate for Thermal Barriers. P. J. Catto.
3C36. Ideal MHD Stability Properties for Highly Elongated Spherical Shell and Racetrack Tokamaks. F. J. Helton and J. M. Greene.
3C37. Manifestly Gauge-Invariant Relativistic Ponderomotive Theory. B. M. Boghosian and A. N. Kaufman.
3C38. Volt Second Consumption due to Sawtooth Activity. W. A. Houlberg.
3C39. Kinetic Field-Reversed Configuration Equilibria. R. L. Spencer, J. L. Schwarzmeier, and J. Albert.
3C40. The Issues of Boundary Conditions and Time Discretization when Simulating MHD Dynamics. A. A. Mirin.

3D POSTER SESSION
11:10-1:10pm PennTop Room South

3D1. PAP: An Apprentice program for Doing Plasma Physics Theory. H. E. Mynick.
3D2. Can Strong ICRH Limit Explain n-mode in RFC-XX-M. P. B. Parks, P. L. Andrews, H. R. Garner, and B. J. Leikind.
3D3. Energy Confinement in v(*i) 1 Plasmas. Z. G. An, P. W. Terry, and P. H. Diamond.
3D4. Nonlinear Plasma Response to Externally Applied Fields in Plasma Simulations. H. C. Huang, V. K. Decyk, R. D. Sydora, J. M. Dawson, and I. Jechart.
3D5. Electron Cyclotron Resonant Heating of Trapped Electrons in Mirror Field. S. P. Kuo, E. Levi, and B. R. Cheo.
3D6. Axial Eigenmodes of Ion Loss-Cone Instabilities in the TARA Plug and Anchor. Y. T. Lau and M. J. Gerver.
3D7. Modeling Power Deposition in ECH Experiments. A. H. Kritz and H. Hsuan.
3D8. Decimation in Turbulence. T. Williams, E. R. Tracy, and G. Vahala.
3D9. Minimum Energy State of MHD Equilibria. J. Y. Hsu and M. S. Chu.
3D10. Three Dimensional Analysis of ICRF Wave Propagation and Antenna Loading Characteristics. R. J. Kashuba, D. Smithe, P. L. Colestock, and T. Kammash.
3D11. Anomalous Current penetration and Oscillating Current Drive in Tokamaks. J. M. Finn and T. M. Antonsen, Jr..
3D12. RF Heating and Cyclotron Instability. B. Hafizi and R. E. Aamodt.
3D13. Anomalously Large Ti/Te Ratios due to E x B Drive. J. R. McNally, Jr..
3D14. Neoclassical Like Impurity Transport in Central Region of Tokamak Theory Versus Experiment. K. W. Wenzel and D. J. Sigmar.
3D15. Stability of a One-Dimensional Plasma in Slab Geometry. T. H. Jensen and W. B. Thompson.
3D16. Dynamics of L-H Transition. S. K. Wong and N. Ohyabu.
3D17. Applications of Neutralized Ion Beams to Magnetic Fusion. N. Rostoker.
3D18. Monte Carlo Simulation of Alpha-Particle Transport in Tandem Mirrors. R. S. Devoto and J. Kerns.
3D19. The m=1 MHD Instability in Tokamaks. A. A. Ware.
3D20. Simulation of Ramped Current Operation in the Reversed-Field Pinch. C. K. Rowdyshrub, E. J. Caramana, and D. D. Schnack.
3D21. Influence of Anomalous Thermal Losses in Ignition Conditions. W. M. Tang and B. Coppi.
3D22. Thermal Effects on Tearing Modes. J. S. Kim, M. S. Chu, and J. M. Greene.
3D23. Relaxed States in Reversed-Field Pinches and Tokamaks. A. Bhattacharjee and E. Hameiri.

3D24. The intrinsic Electromagnetic Solitary Vortices in Magnetized Plasma. J. Liu and W. Horton.
3D25. A Numerical Study of Stellarator Transport. W. N. G. Hitchon and H. E. Mynick.
3D26. Numerical Study of Ripple Transport in a Transport Optimized Stellarator Field. C. D. Beidler, W. N. G. Hitchon, and J. L. Shohet.
3D27. Axisymmetric MHD-Stable Sloshing Particle Distribution Functions. G. V. Roslyakov, N. Dominguez, and H. L. Berk.
3D28. Anchor Stabilization of Trapped Particle Modes in Mirror Machines. H. L. Berk and G. V. Roslyakov.
3D29. The Trapped Particle Effect on Diamagnetic Limit in Hot Electron Physics. Y. Z. Zhang and H. L. Berk.

3E SUPPLEMENTAL AND POST-DEADLINE POSTER SESSION
11:10-1:10pm PennTop Room South

3E1. Possible Candidate Microinstability for Anomalous Electron Transport. B. Coppi and F. Pegoraro.
3E2. Theoretical Model of Fishbone Oscillations. B. Coppi and F. Porcelli.
3E3. The Global MHD for Circular and Highly-Elongatd Tokamaks with Magnetic Separatrices. J. K. Lee.

PARTICLE TRANSPORT IN TOKAMAKS

A. WOOTTON

FUSION RESEARCH CENTER
UNIVERSITY OF TEXAS, AUSTIN, TX

COMPOUND SAWTEETH IN TOKAMAKS

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College Park, Maryland 20742

A detailed study of sawteeth 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. The value of the perpendicular thermal conduction near the magnetic axis is found to control the structure of the sawteeth. In discharges with good central confinement, skin currents form at a finite radius causing the safety factor q to fall below one away from the magnetic axis. Both normal[1] and compound[2] sawteeth are produced with features commonly observed in experiments: long successor oscillations following the subordinate crash, continuous m=1 activity, hollow temperature profiles after the main crash. Important new conclusions are: (1) sawtooth crash times can occur on an MHD time scale; and (2) when skin currents are present the effects of the resistivity gradient are found to remain important even at very low values of resistivity (high temperature). Simple explanations of experimental observations are given.

1. S. Von Goeler, W. Stodiek, and N. R. Sauthoff, Phys. Rev. Lett. 33, 1201 (1974).
2. W. Pfeiffer, Nucl. Fusion 25, 673 (1985); S. B. Kim (private communication); H. Yamada, K. McGuire, et al., PPPL Report #2213.

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

β LIMITS IN RACETRACK-SHAPED TOKAMAKS

A.D. Turnbull, R. Gruber, S. Nicli, A. Roy, O. Sauter and F. Troyon

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Association Euratom - Confédération Suisse
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ABSTRACT

The n = 1 free boundary kink mode imposes important limitations on both the current configuration and the attainable β in tokamak plasmas. The n = 0 axisymmetric mode imposes further constraints on the current profile if the poloidal cross-section is elongated. Large n ballooning modes place further limits on the β. All of these constraints become more severe with increasing elongation of the cross-section.

We present the results of a study of the stability against axisymmetric (n=0), kink (n=1) and ballooning modes of elongated tokamak plasmas, characterised by a racetrack-shaped poloidal cross-section, up to an elongation of 4 to 1. Current limitation studies are used to define operational windows for stability against current-driven kink modes at low β. β optimization studies are used to determine the β limits imposed by the simultaneous requirements of stability to kink and ballooning modes, within the stable operating regime. Wall stabilization studies are presented to examine the feasibility of stabilization of axisymmetric modes by a nearby conducting wall.

(Sherwood Theory Conference 1986, NYC, NEW YORK, USA April 14-16)

Ideal MHD Ballooning Stability in Divertor Tokamaks - a Picture of the H-Mode

C.M.Bishop

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(EURATOM/UKAEA Fusion Association)

One of the most notable features of the H-mode regime in divertor tokamaks is the occurrence, just inside the magnetic separatrix which bounds the plasma, of very steep gradients of temperature and density, and therefore of pressure. We study the stability of such gradients to ideal ballooning modes using a generalisation of the s-α equilibrium appropriate to divertor tokamaks.

Remarkably we find that a non-zero edge current density can lead to coalescence of first and second ballooning stable regions for flux surfaces sufficiently close to the separatrix. The plasma in the edge region is then stable for any value of the pressure gradient. An explanation for this effect is given in terms of the variation of local shear around the flux surface.

These results suggest a possible origin for L- and H-mode regimes. In the L-mode the edge temperature, and hence the current density, is low and the pressure gradient is ballooning limited. In the H-mode the edge temperature is much higher and the corresponding current flow prevents ballooning instability. The edge pressure gradient can now become very steep. The correspondingly higher temperature just inside the separatrix maintains self-consistently the structure of the stability diagram and this leads to the bistable nature of the L-H transition.

SHERWOOD THEORY MEETING 1986

Theory of Ion-Temperature-Gradient-Driven Turbulence and Anomalous Transport in Tokamaks*

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Recent experiments on the Alcator-C tokamak indicate that when the plasma density is large enough so that the electron-ion thermal equilibration time $(\tau_{ei} \sim 1/n^2)$ approaches (from above) the neo-Alcator electron thermal energy confinement time $(\tau_{E_e} \sim n)$, significant anomalous energy loss can occur through the ion conduction channel. The onset of this loss process occurs while τ_{E_e} begins to saturate. This trend appears to extend into auxiliary heating regimes. In particular, recent charge exchange recombination spectroscopy experiments on the D-III tokamak during neutral beam injection have resulted in direct measurements of the magnitude and radial profile of the ion thermal diffusivity $\chi_i(r)$. Substantial departures, in both magnitude and profile shape, from the neoclassical χ_i prediction are indicated. Since these experimental results suggest that an important relationship between particle and energy confinement exists, it is vitally important to understand the physical processes responsible.

Here, we present an analytic theory of saturated ion-temperature-gradient-driven turbulence as a possible explanation of the experimental observations. For $\eta_i > \eta_{ic}$, where $\eta_i = (L_n/L_{T_i})$ and η_{ic} denotes the critical value of η_i necessary for instability, the dynamics of ion-temperature-gradient-driven turbulence are described by a simple fluid equations for ion pressure $(\tilde{p}_i)$, parallel velocity $(\tilde{v}_{\parallel i})$, and vorticity equations. For a quantitative understanding, energy-conserving, renormalized spectral energy equations are derived and resulting mode-coupling equations are solved analytically using the spatial representation technique. The calculated wavenumber spectrum of ion pressure fluctuations in a stationary turbulence has the form of $\langle \tilde{p}_i^2 \rangle_{k_\theta} \sim k_\theta^{-5/2}$. The resulting ion thermal diffusivity is $\chi_i = [(\pi/2)\ln(1+\eta_i)]^2 [(1+\eta_i)/\tau]^2 (k_{0\theta}\rho_s)(\rho_s^2 c_s/L_s)$. The most probable poloidal wavenumber $(k_{0\theta}\rho_s)$ is evaluated by taking the rms-value of the k_θ-wavenumber over calculated wavenumber spectrum, and is shown to be weak function of "Reynolds number" and has numerical value of 0.4. The numerical value of χ_i is found to be consistent with experimentally-deduced ion thermal diffusivities. The associated electron thermal diffusivity, and particle and heat-pinch velocities are also calculated. The effect of impurity density gradient on saturated η_i-mode turbulence is discussed and a related explanation of density profile steepening during "Z-mode" operation is proposed.

Finally, relation to the momentum transport[1] in neutral beam heated tokamak and numerical simulation of η_i-mode[2] turbulence will be discussed.

1. N. Mattor and P. H. Diamond in this meeting.
2. J. N. Leboeuf et al., in this meeting.

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

Tokamak Transport Code Simulations With Drift Wave Models*

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Coefficients for the $\widetilde{E}\times B_0$ transport due to the dissipative trapped electron and toroidal ion temperature gradient drift modes are incorporated into a standard tokamak transport code to comprehensively study anomalous energy transport in tokamaks. These mechanisms have little or no intrinsic current (or q) dependence. Acting alone they do not describe the observed shrinkage of temperature profiles at high q nor the favorable current scaling of beam heated discharges. Following Perkins,[1] it is necessary to include some mechanism to degrade the edge confinement with increasing q. We consider the transport from collisional drift modes and a model for the effects of low-m tearing modes. The simulations then show shrinkage at high q and a high degree of profile consistency. In the ohmic regime the model obtains low density neo-Alcator scaling and at high density the ion temperature gradient mode contributes strongly to the saturation of the energy confinement time. In the beam heating regime, the model obtains an energy confinement time with weak density and magnetic field dependence, degradation with power and favorable current scaling as experimentally observed. The study concentrates on limiter DIII discharges, but improved confinement in divertor discharges is also discussed. The generality of the drift wave model is further tested by simulating smaller tokamaks (ISX-A, Alcator-A, and Alcator-C) as well as the largest tokamak, JET. In addition, the drift wave model is used to predict possible methods for improving confinement in tokamaks.

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

[1]F.W. Perkins, in *Proceedings of the 4th International Symposium on Heating in Toroidal Plasmas*, Rome (1984) p. 97.

PHYSICS AND DESIGN ISSUES FOR IGNITION EXPERIMENTS*

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Ignition experiments that are capable of testing the confinement of the charged products for both D-T and D-He^3 reactions, requiring plasma currents typically larger than 6 MA, have been analyzed and found to be feasible. A parameter of merit that is considered to be indicative of the plasma thermal energy confinement is the product $I_p\bar{\bar{B}}_p$ where I_p is the plasma current and $\bar{\bar{B}}_p$ the mean poloidal field. Thus $I_p\bar{\bar{B}}_p \simeq 40$ MA-T has been taken as a design objective with $I_p \gtrsim 10$ MA. Among various experiments that can have the highest values of $I_p\bar{\bar{B}}_p$ we consider those with the highest values of $\bar{\bar{B}}_p$, that is with the highest fields and most compact dimensions, to be capable of approaching ignition conditions with the highest plasma densities and the highest current densities. This corresponds to maximizing also the rate of ohmic heating and α-particle heating. By optimizing the characteristics of low aspect ratio, elongated plasma equilibrium configurations ($R/a \simeq 2.7$, $b/a \simeq 1.7$) and the structural features of the magnet systems capable of producing them, we have shown that experiments with $\bar{\bar{B}}_p \simeq 38$ kG, $I_p > 10$ MA and $q_\psi \simeq 2.5$ are feasible. In this case ignition can be attained with a considerable margin against presently known finite-β limits and within the limits of stability of ideal MHD internal kink modes. Taking into account that the heating phase cannot be described as a sequence of steady state conditions, the role of ohmic heating can be enhanced by appropriate programming of the plasma current and of the particle density, and auxiliary heating is relegated to a function of back up against an excessive deterioration of the plasma confinement properties.

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

Alpha Particle Heating in the FPD Mirror Central Cell*

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Both analytic and Monte Carlo methods have been developed to provide realistic tools in studying the alpha particle heating in the central cell of the FPD (Fusion Power Demonstration) tandem mirror configuration. Of particular interest was the effect of the motion of fast alpha particle on the radial diffusion in the FPD central cell. The effective electric field generated by an alpha particle gyrating at its finite Larmor radius and the effective potential obtained from the canonical angular momentum were considered in determining the fraction of alpha particles which were radially confined. The numerical Monte Carlo, Fokker-Planck code was also developed, by utilizing the alpha particle source function in phase space and the Fokker-Planck collision operator, to determine the alpha particle heating in the central cell. Both power depositions obtained by the Monte Carlo and the analytic methods are in reasonable agreement and this suggests that, in some cases, an analytic method can provide a valuable tool in evaluating the alpha heating in the tandem mirror central cell.

*work supported by the FEDC/ORNL.

MHD CURRENT GENERATION: ELONGATION PUMPING AND TRANSFORM CONTROL*

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Nonlinear beating of time-harmonic modulation of poloidal and toroidal fluxes has been proposed as an RFP/tokamak current drive scheme. We explore several possible embodiments of this idea, utilizing the proposed low aspect ratio (low TF inductance) device STX.

Radial modelling describing simultaneous evolution of poloidal and toroidal magnetic fields, temperatures, and densities, predicts that reasonable device parameters ($\delta V_{loop} \sim 10$ V, $\delta B_{toroidal} \sim 0.05$ T) would suffice for an experimental test of the scheme. Penetration to the axis of the skin current produced by the method is an important issue. A new approach is studied which employs simultaneous modulation of elongation and B_T. These two low inductance elements can produce the same nonlinear mode effect, and 1-1/2D modelling suggests that an experimental test is also feasible for this scheme.

We also describe recent results in the closely related area of MHD current generation in stellarators. 3D coupled transport equilibrium calculations show that programming the external vacuum boundary in time can be used for rotational transform control. This corroborates earlier results obtained at ORNL using flux controlled sequences of equilibria.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.

SHERWOOD THEORY MEETING 1986

Structure and Dynamics of Coherent Structures in Tokamak Edge Turbulence*

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Recent data[1] from studies of tokamak edge turbulence suggests that coherent structures, referred to as density blobs, may play a role in edge plasma dynamics. Here, we seek to characterize the structure of density blobs and to understand their nonlinear dynamics i.e., instability mechanisms.

An isolated fluid blob in a magnetized incompressible plasma can be characterized as the 'most probable' state of localized configuration space density perturbations using entropy arguments. Blob structure is determined using the Maxwell-Boltzman and box-blob models. The blob size, effective temperature, and other relevant quantities of interest are calculated and related physics issues such as blob shielding and critical temperature for blob formation are elucidated. Then, comparisons with the results of a theory of edge turbulence which uses a closure approximation[2] are made.

The nonlinear blob growth rate is derived and relevant physical growth and saturation mechanisms are identified and discussed. In particular, a novel nonlinear instability mechanism, whereby blobs grow by reflection off neutralizing density perturbations is proposed. Finally, the effects of blob-blob collisions and intermittency, as well as comparisons to drift-hole results,[3] will be discussed.

References

1. S. J. Zweben, Phys. Fluids **28**, 974 (1985).
2. P. W. Terry and P. H. Diamond, Phys. Fluids **28**, 1419 (1985).
3. P. H. Diamond, T. S. Hahm and P. W. Terry, Sherwood Theory Meeting 3B-5 (1985).

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

COMPARISON OF VARIOUS THERMAL CONDUCTION MODELS IN THE PREDICTION OF DENSITY LIMITS IN TOKAMAKS

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We compare four thermal conduction models in determining the density limit for ohmically heated tokamaks using our earlier developed catastrophe scenario.[1] Using profile consistency arguments we derive expressions for the density limit in terms of plasma current, z_{eff}, major radius, minor radius, toroidal field, and ion mass. Taking data from ten different tokamaks we compare the calculated density limits for the four models with the experimental observations.

1. P. N. Guzdar, Phys. Fluids 27, 447 (1984).

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

MHD Smorgasbord

J.P. Freidberg
MIT Plasma Fusion Center

Three separate results are discussed which are of interest to the fusion community, particularly those involved in MHD equilibrium and stability theory.

1. One puzzle that has appeared recently in the study of MHD β limits in a tokamak is the linear scaling of β with $1/q$ observed in the Sykes limit and the Troyon limit. General dimensional arguments indicate that the appropriate scaling should be $\beta \sim 1/q^2$. It is shown by simple arguments that, contrary to first appearances, both results are compatible.

2. A simple calculation is presented which calculates the stability, including growth rates, of a general diffuse screw pinch surrounded by a resistive wall. The connection between the ideal situation, with and without a perfectly conducting wall is demonstrated explicitly. An examination of the spectrum of resistive wall instabilities shows that neither plasma rotation nor finite Larmor radius effects can stabilize these modes.

3. The formula for the vertical field required to hold a tokamak in equilibria, first derived by Shafranov, has proven extremely useful in the design and operation of tokamak experiments. Even so, in its usual form, the physical significance of each of the terms is not immediately apparant. An alternate form of Shafranov's relation is presented in which the separate physical effects entering toroidal force balance are explicitly delineated.

PRACTICAL GENERALIZED ENERGY PRINCIPLES FOR DETERMINING LINEAR AND NONLINEAR STABILITY

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We present generalizations of the ideal MHD energy principle, δW, for fluid and kinetic models, that can handle equilibrium flow and FLR effects. The usual energy principle arises because the Hamiltonian has standard kinetic energy and potential energy terms, in which case stability is determined by the potential alone. More generally in Hamiltonian systems, the total energy can serve as a Liapunov functional. Although the Hamiltonian structure of continuous media expressed in Eulerian variables is not of the canonical form, it still has this built in Liapunov functional feature. There is a generalization of the Hamiltonian, a generalized free energy (F), that has equilibria as stationary points and for which definiteness of the second variation, δ^2F, is sufficient for stability. This definiteness of δ^2F is a more dependable criterion for practical stability than conventional linear spectral stability. Indeed, sometimes linear theory is highly misleading because nonlinear instability for arbitrarily small pertubations can arise. This can occur only when δ^2F is indefinite. We will show that δ^2F - not the second variation of the physical energy-is the appropriate perturbed energy. When δ^2F is indefinite there exists either instability or a negative energy mode (direction in function space). (Comparison with the Sommerfeld-Brillouin condition, $\omega\partial\varepsilon/\partial\omega < 0$, will be made.) The later can result in explosive instability even though spectral theory indicates stability. One can use δ^2F in much the same spirit as δW ; i.e. insert trial functions and then vary parameters to search for indefiniteness. A further test is used to distinguish linear instability from negative energy directions. We emphasize that δ^2F is applicable even if the dielectric functional is intractable or not even defined. We will present examples. In particular we find that the δ^2F velocity threshold for the warm two-stream instability is lower than that of conventional linear theory. We also examine some MHD equilibria with flow and FLR effects.

Sawtooth Oscillations and Transport in Compact Ignition Tokamaks

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Large sawtooth oscillations are observed to play a dominant role in transport simulations of compact ignited tokamaks. These sawteeth are particularly broad (with mixing radius up to 70% of the plasma halfwidth) because current is being maximized in a plasma with elongated cross section. There are steep gradients and high shear between the edge of the mixing region and the edge of the plasma. After each sawtooth crash, the change in internal inductance produces a negative current density spike at the edge of the mixing region, which leads to rapid local changes in the current profile in these simulations. Most of the Ohmic heating occurs near the edge of the mixing region. Most of the alpha heating in these ignited plasma simulations, occurs within the mixing region and greatly enhances the amplitude of the temperature sawtooth oscillations. After ignition, the steep pressure gradients off the shoulders of the mixing region after each sawtooth crash are large enough to drive local ideal ballooning modes. The temporarily enhanced transport in these regions, together with the large fluctuations in alpha heating power, produce rapidly changing profiles.

Different transport models (thermal conductivities with different radial dependence) produce current profiles with only mildly different sawtooth mixing radii. Rapidly ramping the current can delay the onset of sawtooth oscillations, but so much current is needed in these devices that it is difficult to avoid sawteeth before ignition. Once sawtooth oscillations start under these conditions, the mixing radius rapidly spreads to its steady state value.

Work supported by U.S. DOE contract No. DE-AC02-76-CHO-3073.

RADIAL ELECTRON TRANSPORT ASSOCIATED WITH FAST WAVE CURRENT DRIVE*

D. Jovanović and G.J. Morales

Department of Physics

UCLA

An analytical study is made of the radial electron transport caused by a fast Alfven wave propagating unidirectionally, as is characteristic of current drive experiments. A collisionless drift kinetic equation is used to describe the slow time evolution of the electron distribution function in the presence of a Landau damped fast wave. The intrinsic radial transport results from the combined effects of $\underline{E} \times \underline{B}_0$ drift due to the wave electric field $\underline{E}$, and the simultaneous radial electron flow produced by the radial component of the wave magnetic field, which for the electrons acts as a low frequency magnetic perturbation. For the nonresonant particles, the drift kinetic equation is solved using the quasilinear approximation, while for the resonant trapped and resonant passing particles, the integration is performed along generalized characteristics. The time asymptotic distribution function for these three classes of particles is found and the consequent modifications in the density and current drive profile are obtained.

*Work supported by USDOE.

THEORETICAL STUDIES OF LOWER HYBRID CURRENT DRIVE IN THE VERSATOR II TOKAMAK*

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Recently, steady state current drive has been demonstrated[1] in the Versator II tokamak using driven lower hybrid waves at f_o = 2.45 Ghz, up to line average electron densities of $\bar{n}_e \lesssim 1.2 \times 10^{13}$ cm^{-3}, and with efficiency $\tilde{\eta} = n_e$ (10^{14} cm^{-3}) I_p(kA) R_o(M)/ P_{in}(kW) $\approx$ 0.0072. In order to understand the wave propagation and wave absorption physics in this experiment, we have applied a simulation model[2] for lower hybrid current drive which incorporates a toroidal ray tracing code and a steady state, parallel velocity Fokker Planck calculation including the effects of finite electron tail confinement and a large perpendicular electron temperature due to pitch angle scattering. Because of the low electron temperatures in Versator ($T_{eo} \lesssim 250$ eV), values of parallel refractive ($n_\parallel = k_\parallel c/\omega$) in excess of 12-15 are required for electron Landau damping and subsequent RF current generation. Although most of the injected RF power is characterized by $n_\parallel \lesssim 5$, it is found that increases in $n_\parallel$ due toroidal geometry effects are sufficiently large so as to cause a significant Landau interaction.[2] Also the presence of low amplitude power at $12 \lesssim n_\parallel \lesssim 15$ in the injected RF power spectrum is found to be important in reproducing the experimentally observed values of $\tilde{\eta}$. It is found that the order of magnitude lower current drive efficiency in Versator II, relative to that in Alcator C and PLT ($\tilde{\eta} \lesssim 0.1$), can be attributed to a combination of effects, including reduced wave accessibility, poorer electron tail confinement, lower electron temperature and increased collisional damping, and larger negative RF current generation due to waves at $n_\parallel < 0$.

[1]M.J. Mayberry et al., Phys. Rev. Lett. 55, 829 (1985).
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*Work supported by the U.S. Department of Energy
Contract No. DE-AC02-78ET51013

RADIAL LOCALIZATION OF DRIFT CONE AND ION-CYCLOTRON LOSS CONE MODES

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The radial structure of the DCLC modes in an axisymmetric mirror (like MIX-1) has been modelled by an integral equation in Fourier space. The solutions to this integral equation reproduce the experimentally observed radial structure quite accurately. To provide an understanding of the results we have developed a WKB code (using R. Littlejohn's formulation). Detailed results of our integral equation as well as the WKB code will be presented.

Work was supported by the National Science Foundation.

Nonlinear Model for Drift Wave Turbulence

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A key question for drift wave turbulence models of tokamak confinement is: Does the saturation level of drift waves depend on the global magnetic geometry via q and s, in addition to the local density and temperature gradients? This work shows how a simplified-but-realistic, nonlinear, toroidal drift wave problem can be reduced to a set of three coupled scalar partial differential equations, first order in time, which satisfy periodic boundary conditions. Appropriate scalings of length, time, and dependent variables make all terms of order unity. These equations are well-suited for computational solutions via three-dimensional spectral methods; a $(64)^3$-mode code should provide good accuracy. The important nonlinearities are of the $-(c/B)\vec{\nabla}_{\perp}\phi\times\hat{b}\cdot\vec{\nabla}_{\perp}$ type and occur in equations for the ion polarization drift,[1] parallel ion velocity, and trapped electron density. Mathematically, the nonlinear operator couples linear solutions of even and odd parity about a rational surface, suggesting mode-coupling to odd modes with high shear damping as the principal saturation mechanism. With good fortune, initial computational results may be available.

*1985-86 JILA Visiting Fellow.

[1] A. Hasegawa and K. Mira, Phys. Fluids 21, 87 (1978).

PASTUKHOV PROBLEM IN TOROIDAL DEVICES*

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When high energy particles in a plasma hit a wall, they leave a loss region in velocity-space. The existence of a loss region is expected to have an influence on the edge plasma behavior in toroidal devices with high temperature ions and a boundary wall close to the limiter-defined plasma edge. High energy particles near the plasma center can also lead to such effects.

To construct the velocity-space particle loss rate expression from an approximate solution to the high-velocity expansion of the linearized Fokker-Planck equation which vanishes on the loss boundary, a variational principle is used to find the lowest normal mode. Because of the complicated shape of the loss region (no azimuthal symmetry in velocity space), the fictitious source method by Pastukhov[1] cannot be used.

From the quasineutrality of the plasma, a consistent ambipolar electric field is found in both slab and cylindrical geometries.

The effect of this velocity-space loss region and the ambipolar electric field on the RFP (parallel component of the Ohm's law) and the Octupole (reduced diamagnetism) will be discussed.

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*Work supported by NSF Grant #PHY-8306845 and U.S. DOE Grant #DE-FG02-86ER53218.

[1]V.P. Pastukhov, Nuclear Fusion 14, 3 (1974).

MULTIPLE-WAVE CALCULATIONS OF WAVE-DRIVEN MHD EQUILIBRIA*

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ABSTRACT

Our previous calculations of toroidal MHD equilibria determined consistently by wave-driven currents[1] have been extended to include currents driven by a spectrum of waves. Allowing more than a single wave provides the flexibility to more nearly match given, desired equilibria and more nearly describes the launchers in a realistic experiment. In particular, we have been able to determine wave spectra that match a selection of moderate-beta, reactor-relevant equilibria to the order of one percent in quantities such as beta, plasma current, and safety factor profile. In order to do this it has been necessary to include both fast waves for current drive in the bulk of the plasma and slow waves (lower-hybrid) to get current near the edge. In addition, high-beta equilibria can be produced. Results of these calculations will be presented including the power required to drive the various equilibrium configurations.

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* Work supported by the U.S. Department of Energy/Office of Fusion Energy.

ICRF Wave Coupling and Antenna Design with High Beta Tokamak Equilibria*

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Maxwell's equations are solved in 2-D for the electromagnetic fields in a toroidal cavity using the cold plasma fluid dielectric tensor in the Ion Cyclotron Range of Frequencies. The vector wave equation is reduced to a set of two, coupled second-order p.d.e.s that are finite differenced. Dissipation is modelled via a small heuristic collision frequency. Realistic magnetic field geometry effects are introduced through the use of model tokamak equlibria. This code can be applied to the study of power coupling of a wave launcher in a tokamak. The impact of toroidicity, rotational transform, plasma collisionality, composition, and antenna configuration to ICRF wave coupling and power absorption shall be discussed. This study is a continuation of previous work.[1]

*Supported by DoE Contract Nos. DE-AC02-76ET53016 and DE-AC02-76-CHO-3073.

[1]R. S. Elet, et al., Bull. Am. Phys. Soc., 30, 1571.

SHERWOOD THEORY MEETING 1986

"Half-Implicit" Guiding Center Electrostatic Particle Codes *

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Electrostatic particle codes with guiding center electrons and full dynamic ions have so far relied on a predictor-corrector particle pushing scheme for stability and accuracy with large time steps.[1] This means calculating the electron charge density and potential, as well as forces, twice per time step and pushing the electrons twice per time step because positions and velocities are known at staggered time steps.

Recently an algorithm, termed the "half-implicit" pusher,[2] was devised where positions and velocities are known at the same time step. Its performance is equal to leap-frog pushers in accuracy with slight time savings. However, when applied to guiding center codes, the "half-implicit" algorithm only requires one push of the electrons and only one calculation of the density, potential and forces per step. The accuracy for as large a time step turns out to be comparable to the cumbersome predictor-corrector algorithm with savings of a factor of 2 in run time in $2\frac{1}{2}$D. If the tests hold out, we should be able to realize significant savings of memory and computer time in 3D.

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

Transport Simulations of TFTR Ohmic Plasmas*

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The BALDUR time dependent transport code[1] is used to simulate TFTR ohmic plasma experiments with a microinstability-based model for χ_e[2]. The electron temperature profiles of low radiation deuterium plasmas are found to be well described by this model when the plasma has reached ohmic equilibrium. The model is not designed to simulate the transient evolution of the temperature profiles during current ramp. The temperature profiles agree well with TVTS data for experiments with electron density in the range $2 \times 10^{13}\mathrm{cm}^{-3}$ to $5 \times 10^{13}\mathrm{cm}^{-3}$.

For plasmas with more than 60% radiation loss, a modification of the model is proposed:

$$\chi_e = \frac{1.6 \times 10^4 C_\mu^{0.4} \alpha_n^{0.2} B_T^{0.3} a Z^{0.2}}{R^{1.9} q_a^{1.6}} F_H$$

where

$$F_H = \frac{\left(1 - e^{(-q_a+0.5)}\right) e^{2/3(q_a+0.5)r^2/a^2} \int_0^{r/a} dx\, x\, h(x)}{r^2/a^2 (n_e(r)/n_0) \int_0^1 dx\, x\, h(x)}$$

and $h(x)$ is defined as the total energy deposition profile including ohmic heating minus radiation losses. Simulation results will be compared to experiment.

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*This work supported by U.S. DoE Contract No. DE-AC02-76-CH0-3073.

**Also at Hunter College, New York, N.Y.

[1]C. E. Singer et al.,BALDUR: A One-dimensional Plasma Transport Code, PPPL-2073 , to be published, 1986.

[2]W. M. Tang, Microinstability-based Model for Anomalous Thermal Confinement in Tokamaks, PPPL-2311.

STUDIES OF NEOCLASSICAL EQUILIBRIUM DISTRIBUTION FUNCTIONS FOR STELLARATOR AND BEAN-SHAPED TOKAMAK PLASMAS*

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The complex geometry of a stellarator magnetic field results in numerous regimes of trapped and untrapped particles. We use the neoclassical transport code DKES (S. P. Hirshman, et al., submitted to Physics of Fluids) and model stellarator B fields to calculate particle distributions $f(\theta,\zeta,\alpha)$ as a function of poloidal, toroidal, and pitch angles. These distributions are analyzed to study the physical effects associated with stellarator transport. Some of these are:

1. The effect of collisionality, and the relationship between the transition from collisionless to collisional plasma and the transit and electric drift times.
2. The breakdown of the validity of bounce averaging in a helical well as the toroidal field periodicity N becomes small.
3. Details of the various trapped and untrapped regions, and the coordinate representations which can be used to exhibit them.

We also investigate distributions $f(\theta,\alpha)$ for bean-shaped tokamak plasmas (see paper by E. C. Crume, Jr., et al., at this meeting) to elucidate the spatial variation of trapping regions, from the outside to the inside of the tokamak as a function of increasing "beaniness."

*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.

Analysis of radial transport and Ohmic heating of a confined plasma.

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We address the problem of radial transport of a low-β confined plasma. Analysis is presented of an ohmically heated plasma (a long time evolution of mass energy and poloidal component of the field). It reveals, among other things, that

1) In a circuit, in which the external current (voltage) is controlled, thermal stability may be always (never) achieved.

2) It provides an upper limit on the rate in which current may be deposited into the plasma (in terms of particles deposition rate) as to avoid the formation of skin current [ex.; if in a classical plasma, particles are recircled $I(r = a,t) < \sqrt{t}$.]

Without heating, plasma relaxation, depending on the assumed transport coefficients, follows one of the following patterns, unique (so far) to plasma,

A. 1. Diffusion rate is geometry independent

   2. Diffusion rate depends weakly on geometry (e.g. fully collisional case).

B. For certain transport coefficients, fast diffusion of mass (heat) blocks the diffusion heat (mass) and unlike case A, here the process always remembers some of its initial data.

SAWTOOTH OSCILLATION STUDIES*

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Various phenomena of sawtooth oscillation are studied using a resistive MHD code. Successive sawtooth cycles (both simple and compound sawtooth) are reproduced in the simulation. However, the anomalous fast crash time seen in many recent experiments is not yet completely understood. The followings are general characters of sawtooth oscillation which can be understood from the simulation.

- The q value at the axis reaches its minimum typically at about .98 during sawtooth oscillation, giving very low shear inside the q=1 surface at all times.
- Due to this flat q profile, a peaked temperature profile before the crash results in a hollow profile after the crash.
- A more peaked heat deposition profile produces a compound sawtooth rather than a simple sawtooth.

Recently, sawtooth oscillation has been found to be stabilized in lower hybrid driven PLT experiments. A possible stabilizing mechanism is presented assuming the stability of runaway component.

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

ABSTRACT SUBMITTED FOR THE SHERWOOD THEORY CONFERENCE

APRIL 14-16, 1986

NEW YORK, NEW YORK

Stochastic Motion of a System with Two Degrees of Freedom Induced by Two Perturbing Waves

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The equations describing the phase space motion of a nonlinear oscillator perturbed by two or more waves of different and, generally, incomeasurable frequencies and wavelength are studied within the framework of the Hamiltonian formalism of systems with two degrees of freedom and by computer simulation. A special technique based on "freezing" the phase difference between the perturbing wave (in the case of two waves) is adopted in studying the surfaces of section and deriving the resonance overlap conditions. Problems, such as the motion of a charged particle trapped in a toroidal magnetic field and perturbed by simultaneously acting electromagnetic waves or by magnetic field perturbations are studied.

MOVING FINITE ELEMENT SIMULATION OF THE FIBER-INITIATED DENSE Z PINCH*

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The Los Alamos fiber-initiated dense Z pinch experiment is a novel approach to fusion which offers the hope of small size, low cost, and simple physics and engineering.[1] The MHD instabilities of early snowplow Z pinches are avoided by starting with a narrow current channel and staying close enough to pressure balance to maintain a smooth pressure profile. The problem of quenching by inrushing cold gas, found in experiments with a laser-initiated channel in a cold dense gas, is eliminated by initiating the discharge with a fiber of frozen deuterium in a vacuum, 20 microns in radius and 5 cm in length. Experiments have achieved $T_e = 300$ eV and $n\tau = 10^{13}$ simultaneously, with no gross instabilities until late in the discharge. The difficulty of diagnosing the experiment and the need to plan scaled-up versions make numerical simulation desirable. An adequate dynamical model must permit the determination of a smooth pressure profile, precluding finite jumps in physical quantities at the plasma-vacuum interface while requiring the treatment of the high vacuum beyond the plasma without numerical difficulties. A narrow boundary layer at the plasma edge, where the conductivity drops from finite to zero, as well as substantial expansion and contraction of the plasma, place severe demands on conventional fixed-grid numerical techniques. The 2500-to-1 length-to-radius ratio and the observed lack of gross instabilities make a 1-dimensional simulation meaningful. The very high density of the plasma makes a fluid model appropriate. A 1-D fluid code using the new technique of moving finite elements[2] has been developed. This method is very fast and accurate, and eliminates long-standing numerical difficulties. It promises to be applicable to a wide range of plasma simulations, including 2- and 3-D problems. Numerical methods will be discussed, and results will be presented.

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*Work performed under the auspices of the USDOE.

Modeling of Electron-Cyclotron Heating in Tandem Mirrors*

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We discuss improvements to the ECH package in the MERTH tandem-mirror modeling code. The ECH package traces rays from various kinds of launchers and calculates the power absorption along the rays and within each flux tube.

The equilibrium magnetic field is calculated for realistic coil configurations by retrieving spline coefficients from a run of the EFFI code for a near-axis field line. This information is combined with pressure profiles to provide a low-β, long-thin approximation to the equilibrium field. For sufficient accuracy of the mod-B surfaces, we include terms of orders zero and one in the long-thin expansion.

From the absorption data along the rays and the power profile of the launcher, we calculate the power deposition profiles as a function of flux-tube radius and azimuthal angle.

To handle absorption (or emission) in anisotropic, non-Maxwellian plasmas, we incorporate a new evaluation of the Hermitian part of the conductivity tensor for a plasma with an arbitrary electron distribution function.

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* Work performed for U.S.D.O.E. by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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§ Science Applications International Corp., La Jolla

SINGLE PARTICLE SIMULATION OF RF DRIFT PUMPING IN PHAEDRUS-B*

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RF drift pumping in Phaedrus-B is investigated by numerical simulation of ion orbits. The magnetic field is computed using the paraxial approximation; a simple model is used to approximate the oscillating electric and magnetic fields due to the antennas. Axial and radial potential gradients are included in the model. Pumping rates and trapping currents can be estimated from the orbit calculations. It is found that both bounce and azimuthal drift resonance effects contribute to the pumping rate. Results will be reported on.

*Work supported by U.S. DOE Grant #DE-FG02-86ER53218.

Energy Principle for Toroidal Plasma with Boundary Effect*

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As one step to combine the transport process with the MHD analysis for the determination of stable equilibria, energy principles in three typical timescales longer than the ideal MHD timescale[1] are developed by using the Hamada coordinate and introducing contribution functions into the global constraints on mass, entropy, and magnetic fluxes (helicity). A generalized fundamental global invariant on magnetic fluxes is shown to include both the Taylor global invariant on the helicity and the Kadomtsev global invariant on the helical flux. The resultant stationary states of equilibria naturally satisfy the experimental boundary conditions at the wall. The stability conditions for the three typical timescales are derived by using the second variations of free energy functional. The transport process is to be included in the present theory of energy principles through the contribution functions in the global constraints on mass, entropy, and magnetic fluxes implicitly. The stability conditions are formulated in general so that both effects of resistive plasma and resistive wall can be included in the stability analysis.

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

†On leave from the Department of Electronic Engineering, Gunma University, Kiryu, Gunma, Japan.

[1]Y. Kondoh, J. Phys. Soc. Jpn. **54**, 1813 (1985).

TRAPPED ELECTRON EFFECTS ON ANOMALOUS ION HEAT TRANSPORT*

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Ion temperature gradient driven instabilities, characterized by the ion mixing mode[1], have long been known to be a cause of anomalous ion heat conduction and are candidates[2] for degraded confinement in torodial devices. Past simulations have found that this mode often influences the transport in only a limited region of a tokamak plasma, since it requires the ion temperature gradient parameter $\eta_i = d\ln T_i/d\ln n_i$ to exceed a threshold value for mode growth that is determined by physical variables. In the presence of a trapped electron population $(n_t/n \sim (2\varepsilon_o)^{1/2})$, however, the stability picture changes considerably. Not only is the η_i threshold value for the mixing mode lowered, but the so-called ubiquitous mode[3], propagating in the ion diamagnetic direction, can also become unstable. These effects, along with the stabilizing tendency of torodial drifts[4] ($\omega_d \sim \varepsilon_o$) near marginal stability, will be investigated and the consequences for transport simulations will be discussed.

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*Work supported by United States Department of Energy

MAGNETICALLY INSULATED IMPACT FUSION

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Recently, a study[1] of the hydrodynamics of impact fusion targets has shown that rectilinear projectile motion may be converted to a spherical implosion, that losses in the metal liner may be acceptably small, and that projectile velocities of $u_o \geq 100$km/sec are required for $Q > 1$. The need to heat the fuel in less than an energy loss (dominated by radiation transport) time τ_E determines u_o. We investigate the possibility of magnetically insulating a lower density fusion target to increase τ_E and reduce u_o to velocities currently available from electromagnetic launcher (rail gun) technology ($u_o \leq 10$km/sec). A similar approach has been investigated for laser fusion targets with encourgaging results.[2]

Plasma formation and confinement in a magnetically-insulated, wall-confined spheromak are discussed. A scheme for helicity injection is presented. Magnetic bias fields are frozen into the rims of colliding shells. Subsequent collision of these shells injects helicity into the spherical cavity between them, forming a low-temperature, high-β, wall-confined spheromak. Compression of such a target in a time less than τ_E heats the plasma adiabatically and confines it by the shell inertia. Ion cross-field thermal conduction is rapid, because of large collisionality in the high density edge required by constant pressure. The ion τ_E scales as $B^{1.4}a^2n^{-.4}T^{-.4}$ and gives an $n\tau_E$ of $5 \cdot 10^{14}$ at 6.5KeV central temperature with an input energy of 150KJ at $u_o = 10$km/sec and a compression ratio of 25. Electron thermal conduction may be close to classical, because of very high density and constant pressure. Effects of electron thermal conduction and radiation transport will be discussed.

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2 A. Hasegawa, et al. Phys. Review Lett. 56, 139 (1986).

"SAWTOOTH" OSCILLATIONS IN FINITE ASPECT RATIO TOKAMAKS*

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The nonlinear evolution of the m/n = 1/1 island is studied for a pressureless plasma in a finite aspect ratio torus. Numerical calculations are performed using the HILO code[1] which solves the resistive MHD equations as an aspect ratio expansion ($\varepsilon = a/R < 1$). The equilibrium used is exact while the linear and nonlinear evolution include terms to $O(\varepsilon^3)$, enough to include toroidal and stochastic field effects. The results are different from those speculated by Lichtenberg[2] for cases where the fields are stochastic around the separatrix. Numerically, the m = 1 island completely reconnects for q(o) as low as 0.6 and aspect ratios down to 4.0 even with large regions of stochasticity.

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

CURRENT RAMP AND IGNITION IN A HIGH FIELD TOKAMAK*

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The effects of the "initial" conditions that are imposed by the evolution of the plasma during the current ramp phase, on the plasma profiles at the start of the current flat top and the consequent effects on the approach to ignition are investigated in a high current, high field tokamak that depends primarily on Ohmic heating. A numerical transport model is used to vary the rise of the plasma current, toroidal field, and particle density and thereby to influence the shaping of the plasma temperature, density, and current density profiles. These are used to control the initial central sawteeth and to optimize the overall power balance and heating during both the current ramp and the following current flat top interval.

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

EFFECTS OF THERMIONIC ELECTRON EMISSION ON THE SHEATH POTENTIAL NEAR THE FIRST WALL

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The sheath potential near the first wall of a fusion reactor can be very sensitive to the temperature of the first wall due to the thermionic emission of electrons. The sheath potential could be lowered significantly due to this effect and the presence of thermionic emission leads to a lower incident energy for the ions impinging on the first wall or limiter and in a reduction in the ion sputtering could result.

The expression for the sheath potential at the first wall in the presence of thermionic emission has been derived. It was found that the value of the sheath potential could be reduced by $\sim 2k_B t_e^{SE}/e$ Volts due to thermionic emission (where k_B is the Boltzmann constant, t_e^{SE} is the electron temperature at the sheath edge, and e is the elementary charge). Thermionic emission is very sensitive to the temperature of the first wall. The transition temperature for a significant reduction in the sheath potential due to thermionic emission was found to be ~1500 K for tungsten and and dependent on the edge density (n_e^{SE}) and temperature (Fig. 1). This transition temperature could be in the range of 700-1100 K for materials with a low work function (~1.5-2.5 eV).

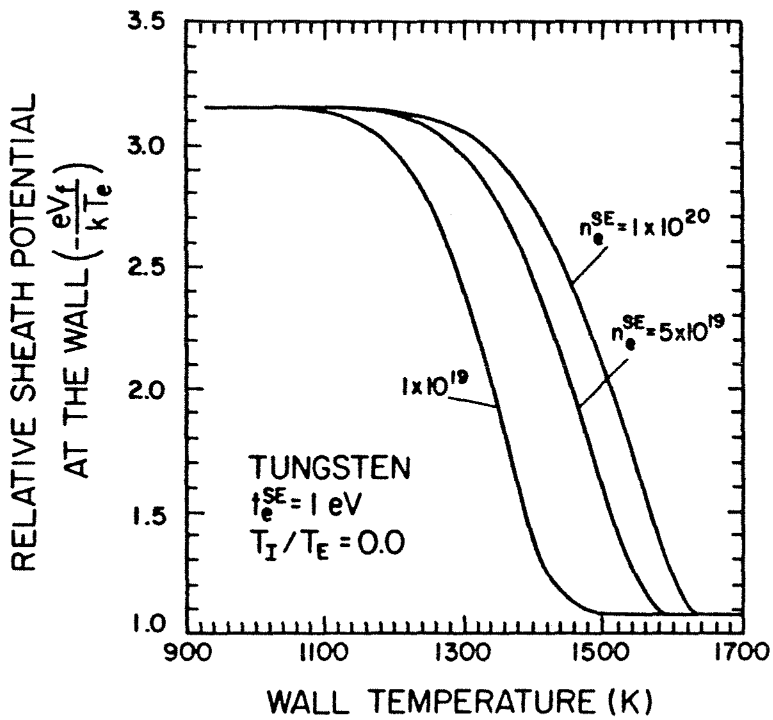

Fig. 1. Normalized sheath potential near the first wall $-\frac{eV_f}{k_B t_e^{SE}}$ relative to the potential at the sheath edge versus wall temperature for sheath edge densities (n_e^{SE}) of 1×10^{19}, 5×10^{19} and $10^{20}\,m^{-3}$ and a sheath edge temperature of 1 eV.

α PARTICLE DRIVEN COMPRESSIONAL ALFVEN INSTABILITY

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The stability of compressional Alfvén waves interacting with energetic α particles is considered. The source of instability is the α particle density gradient making this instability similar to the shear Alfvén instability considered by many others. A basic requirement for tapping the expansion free energy of the α-particles is that the diamagnetic frequency of the α's exceed the mode frequency

$$\frac{\omega_{*\alpha}^2}{k_\perp^2 v_a^2} > 1.$$

This condition is more likely satisfied in high β, low magnetic field configurations. In order that the inverse damping on α's exceed electron Landau damping, a condition on the α density is imposed

$$\frac{n_\alpha}{n_e} > \left(\frac{m_e T_e}{m_\alpha T_\alpha}\right)^{1/2} .$$

A sample calculation for the mode structure will be presented.

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

FULLY-DEVELOPED DRIFT WAVE TURBULENCE

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A pair of nonlinear equations for ϕ, the electrostatic potential and $A_{\parallel}$, the parallel component of the vector potential are obtained for drift waves in a slab model with magnetic shear and valid for $\beta > m_e/m_i$. The electron dynamics is treated in the linear approximation while the ions are treated in the nonlinear fluid approximation. In the $\beta \rightarrow 0$ limit we recover the Hasegawa-Mima[1] equation in the absence of shear and the equation of Tange, Nishikawa and Sen[2] when shear is included. For fully developed ($k_{\parallel} \ll k_{\perp}$) turbulence we have solved these equations using the technique developed by Sudan and Pfirsch[3] and modified by Rosenbluth and Sudan[4]. The power spectrum $I(\underset{\sim}{k}_{\perp})$ of the fluctuations is obtained in terms of linear growth/damping vs $\underset{\sim}{k}_{\perp}$. The width of the spectrum $I(\underset{\sim}{k}_{\perp},\omega)$ in frequency (which exceeds linear damping) is also determined as a function of $\underset{\sim}{k}_{\perp}$. The effect of wave scattering into $k_{\parallel}$ has been accounted for by a nonlinear diffusion operator[4] with a diffusion coefficient determined by the power spectrum. It is shown that the spectrum is unaffected by a weak magnetic shear below a critical threshold.

* Work supported by Department of Energy and National Science Foundation.

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THE INFLUENCE OF END-PLATE POTENTIAL CONTROL ON MHD STABILITY AND DRIFT PUMPING IN MIRROR PLASMAS*

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By adjusting the electrostatic potential on the end plates of a mirror plasma, the plasma's MHD stability can be altered. Furthermore, the plasma's MHD response to low-frequency modulation of the end plates can be used to pump unwanted ions that collect in a thermal barrier. Here, we derive precise boundary conditions for the MHD stability equations to model an end plate separated from the plasma by a sheath. We show how these conditions can be used to relate the end-plate potential to probe measurements of internal plasma displacements in order to study the problem of feedback stabilization of ballooning, interchange and rotational modes. We also calculate the low-frequency driven MHD response to end-plate-potential modulation and the concomitant resonant diffusion.

* Work performed for U.S.D.O.E. by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

1986 SHERWOOD THEORY CONFERENCE
April 14-16, 1986; New York, New York

THE ANOMALOUS DOPPLER INSTABILITY DURING LOWER-HYBRID CURRENT DRIVE*

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The anomalous Doppler instability is investigated for two-dimensional velocity distributions $f(v_{\|}, v_{\perp})$ appropriate for lower-hybrid current drive. In this case, in contrast to the runaway electron problem, this mode becomes unstable at high density when the ratio $\omega_{pe}^2/\omega_{ce}^2$ is sufficiently large. Increasing the maximum velocity v_2 of the rf plateau, $v_1 \leq v_{\|} \leq v_2$ is also a destabilizing influence.

In this paper we give expressions for the growth rate of the electrostatic waves obeying the dispersion relation $\omega = \omega_{pe}(1 + \omega_{pe}^2/\omega_{ce}^2)^{-1/2} k_{\|}/k$ employing both analytical expressions for $f(v_{\|}, v_{\perp})$ and numerical solutions for f from the 2-D Fokker-Planck equation. The analytical an numerical results are in close agreement. Furthermore, a relativistically correct necessary condition for instability is found; namely, $\omega_{pe}^2/\omega_{ce}^2 > \dfrac{1}{\gamma_2^2(v_2/v_1 - 1)^2 - 1} > 0$ where $\gamma_2 = (1 - \dfrac{v_2^2}{c^2})^{-1/2}$.

* This work was supported in part by Hydro-Québec Project No. 01844-571-59535 and in part by DOE Contract No. DE-AC02-78ET-51013.

TRANSPORT IN REVERSED-FIELD PINCHES DUE TO THE TURBULENT ELECTRIC FIELD*

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The effect of the mean electric field, generated by resistive MHD turbulence, on the evolution of a resistive plasma is studied in straight, cylindrical geometry in which all mean quantities depend on the radius. The mean electric field, taken to be generated from tearing and resistive interchange modes, is determined self-consistently from theory/1,2/. The Grad-Hogan algorithm/3/, according to which the momentum equation is approximated on the resistive timescale by JxB=grad(P), is used to constrain the evolution of the plasma velocity. Thus, in the present case, transforming the MHD equations to a Lagrangian coordinate system/4/, with time and the poloidal flux as dependent variables, permits all velocity terms to be eliminated. A complete set of diffusion equations for the pitch, density, and pressure profiles, including the effect of the turbulent electric field, has been derived. The important modification to the transport equations due to the turbulent electric field is that the diffusion equation becomes fourth order in the radial flux variable. On a first attempt, the transformed equations are integrated numerically using explicit schemes for the time-dependent equations and a double-sweep method for the force-balance equation. The implications of the results for the observed prolonged sustainment of the reverse field in RFP's will be discussed.

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ANOMALOUS THERMAL CONFINEMENT IN AUXILIARY-HEATED TOKAMAKS*

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A steady-state type transport code, which has successfully modelled the most significant confinement properties of ohmically-heated tokamak plasmas [1], has been extended to study auxiliary-heated discharges. As in the earlier work, the analysis of anomalous thermal losses in both the electron and ion channels takes into account the influence of trapped-electron modes and toroidal ion temperature gradient (η_i) modes. Macroscopic MHD behavior, associated with tearing modes and with sawteeth activity, provides some constraints on the temperature profiles calculated. In addition, a model [2] accounting for the onset of MHD ballooning modes has now been incorporated. An appropriate model for neutral-beam heating deposition profiles has also been introduced into the basic code. Results will be presented and their implications discussed.

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

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ENHANCEMENT OF RADIAL TRANSPORT BY NONLINEAR COLLECTIVE PROCESSES

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When a nonaxisymmetric electric or magnetic field is applied to a cylindrical pure electron plasma, it produces radial transport. While the field may act directly on the plasma particles, an enhanced level of transport is produced when the field drives a linear collective resonance in the plasma. This case has been previously discussed theoretically[1] and observed experimentally.[2] It is also possible for transport to be enhanced by nonlinear collective processes.[3] For example, the field asymmetry can act as a pump which excites daughter modes via a decay instability or, alternatively, it can drive a mode by induced scattering off of particles. Here we discuss the induced scattering process and compare theoretical predictions with recent experimental observations in a pure electron plasma. The experiment involves the unstable growth of an azimuthally symmetric plasma mode and an associated increase in plasma transport. The instability exhibits threshold dependences on field asymmetry amplitude and mode damping rate that are in qualitative agreement with theory. This instability occurs over a wide range of parameters in contrast with the linear resonance[1] and the decay instability[3] which require tuning of parameters in order to satisfy more restrictive matching conditions. Because of this, the induced scattering process may be more important for enhancing radial transport than either the linear resonance or the decay instability. The physical basis for these processes is quite general and may be relevant to other rotating plasma systems such as tandem mirrors.

This material is based upon work supported by the Department of Energy under Grant DOE DEFG 03-86ER53199.

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SHERWOOD THEORY MEETING 1986

Development and Application of a Three-Dimensional Magnetoinductive Particle Code

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We are implementing a 3-D slab incompressible magnetoinductive particle code. A guiding center drift approximation is used for the electron motion perpendicular to the magnetic field with the retention of the full dynamics for the ions. A combination of a two-dimensional grid with a spectral expansion of the exact particle positions in the third dimension is used. The backround magnetic field is primarily in the direction of this third dimension. The results of tests of the code will be presented. This code was developed to perform kinetic simulation of nonlinear kink instabilities. Preliminary results will be discussed.

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* Work supported by the U.S. Department of Energy and National Science Foundation.

New Solutions for Two-Dimensional MHD Equilibria

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The Liouville equation:

$$\nabla^2\phi = \frac{\lambda^2}{8} e^{-\phi}$$

arises as a model equation in the study of two-dimensional MHD equilibria (here ϕ is a flux function for the magnetic field). The "island chain" solution of this equation is well known, and the stability of this special solution has been studied both numerically[1] and analytically[2]. Here we discuss how to construct more general solutions using inverse scattering methods. The goal of the present work is to find, analytically, the lowest energy equilibrium configuration and thereby establish its absolute stability. Progress toward this goal will be reported.

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MHD STABILITY IN ELONGATED TOKAMAK DISCHARGES

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A study of ideal MHD stability in elongated tokamak plasmas such as the CIT device is presented. The growth rate of external modes as a function of conducting wall position, and internal mode stability as a function of β, have been obtained for cases ranging in elongation from 1.6 to 2.5. Both the proposed CIT (in its prior ISP incarnation) and the Alcator C-MOD devices are considered. The CIT examples have B_o=10.72 T, an aspect ratio A=3.22, q_e=2.6, and major radius R=1.354 m. The elongation, K, ranges from 1.6 to 2.0, with triangularities, δ, of 0.3 and 0.4. In addition, a diverted discharge has been studied. The C-MOD examples have elongations of 2.2 and 2.5 at A=3.0, R=0.75 m, δ=0.3, B_o=7.5 T and q_e=3.1. The various CIT cases were set to a modified Troyon limit, β =3 I/aB_o, and the C-MOD cases to the sub-critical value, β=1.59 I/aB_o; for I in MA and β in %.

The axisymmetric instability is found to passively stabilize for wall positions displaced between 0.75 and 1.25 plasma minor radii beyond the plasma edge, in the range of K studied. The higher order effect of β on the n=0 growth rate is confirmed, and the effect of triangularity is found to be minimal in this parameter range. It is concluded that the passive stabilization requirements for CIT and C-MOD are not particularly severe, although the more critical issue regarding active stabilization on the L/R time of the structure is unresolved.

The n=1 external kink mode is found to impose a more stringent constraint on the positioning of conducting structure. The K=1.8 CIT case requires a wall on the order of 0.3 minor radii to stabilize this mode. The very large parallel current of the device is likely responsible for this proximate shell.

Internal mode stability for highly elongated discharges is found to correlate well with the Troyon criterion, provided (as noted by Troyon and Gruber) that sufficient triangularity exists to stabilize the axis region against local interchange modes. In practice at high elongation, the triangularity required may be difficult to achieve. For K=3.0, a triangularity of 0.5 is required to recover the Troyon β value. On the other hand, the absolute gain in β due to increased current with K, generally offsets the relative shortfall in the Troyon constant. All the cases studied here used scaled 'optimized' profiles which were internal mode stable above a Troyon constant of 3.

In conclusion, external kink modes would appear to be the most significant ideal MHD stability problem, in terms of limiting β, for high current, highly elongated devices such as CIT and C-MOD. Despite some fall off from the Troyon limit at high elongation due to internal mode instability, adequate β values should be achievable. The requirements on the slower timescale active feedback system, rather than the passive stability of the device, is the principal concern for axisymmetric stability.

INITIAL VALUE APPROACH TO THE MHD FIELD ERROR PROBLEM*

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An axisymmetric plasma equilibrium may be significantly altered by the introduction of magnetic field errors. Particularly vulnerable is a reversed field pinch plasma bound by an imperfect conducting wall. Here we treat the problem of the effects of possible 3D magnetic perturbations on the plasma as an initial value problem. This is significant since the long-time limit of the solutions to the initial value problem may not in general agree with the stationary solutions. For example, the long-time behavior of time-dependent solutions indicates a vanishing radial field perturbation at a singular surface where the safety factor is given by $q = m/n$ (m and n are the poloidal and toroidal mode numbers of the perturbation) whereas the stationary case gives non-zero results, thereby allowing for the possibility of magnetic islands.

For a rotating plasma, stationary field errors appear as finite frequency disturbances. The sources of field errors may then act as RF sources driven by the image currents flowing in the wall due to the large ohmic plasma current. To account for a possible shear Alfvén resonance that might be excited in this way, we employ the set of linearized MHD equations with the inertial plasma response. At the resonance surfaces of an Alfvén wave, these equations have solutions increasing, in the long-time limit, linearly in time and oscillating at the local Alfvén frequency ω_o. When a finite resistivity is introduced, the solutions become purely oscillatory after a critical time is reached. In this scheme, the vanishing of ω_o corresponds to the singularity on the rational magnetic surfaces and is viewed as a zero frequency Alfvén wave. It is thus found that the solutions of the stationary and the initial value problems differ qualitatively as ω_o approaches zero. The initial results are compared for a simple geometry.

*Work supported in part by USDOE and in part by the Research Committee of the University of Wisconsin Graduate School.

Direct Solution for the Power Spectrum of a Chaotic System*

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Deterministic systems which exhibit chaotic behavior are extremely interesting to plasma physicists who must deal with the problems of drift wave (and other) turbulence. The normal approach in the investigation of problems of relevance to fusion machines such as tokamaks is to write the model as a set of coupled nonlinear differential equations in time and wave-number space, integrate the equations forward in time and Fourier transform to find the power spectrum in frequency space. This involves the production and storage of an immense amount of data, whereas often the gross details of the solution are all that is required.

Using a zero-correlation assumption for the elements of a power spectrum in frequency space, which forms a tempered distribution, it is possible to reduce the problem to an algebraic form. We apply our technique to the Lorenz system,

$$\dot{x} = -\sigma x + \sigma y\,, \quad \dot{y} = rx - y - xz\,,, \quad \dot{z} = -bz + xy\,,,$$

and by dealing with the Fourier transformed system we derive analytic formulae for the level of turbulence and the correlation time in the x motion. The correlation time, α, is given by

$$\alpha = \left\{ \left[\frac{2b(r-1)(\sigma-b)}{\pi(\sigma+1)} \right]^{-1/2} - b \right\} ,$$

and the level of turbulence by

$$\langle |x|^2 \rangle = 2b\pi(r-1) \left[1 + \frac{b(\alpha\sigma+1)}{\sigma(\alpha b+1)} \right]^{-1} ,$$

There is excellent agreement with numerical simulations, and we plan to apply our technique to larger problems of more relevance to plasma physics.

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

SHERWOOD THEORY MEETING 1986

Analysis of Runaway Confinement Data From the ASDEX Tokamak*

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Magnetic fluctuations have frequently been associated with confinement degradation during auxiliary heating, and with losses from the $q > 2$ region, in general. Recent results from ASDEX indicate that runaway electron confinement degrades during L-phase, but that runaways are confined during the H-phase.

In this work, runaway confinement data is analyzed to determine the radial correlation length of the underlying magnetic turbulence, using the assumption of thermal loss due to stochastic magnetic fields and a simple model which clarifies and extends previous work.[1] In view of the fact that runaway confinement times are deduced by hard x-ray intensity measurements, they are necessarily global measurements. Thus, we have analyzed the data in the light of competing views of "edge"[2] and $q = 2$ [3] confinement.

Preliminary results indicate that the radial correlation length ($W_\perp$) is approximately .1 cm. Using this value, a magnetic fluctuation level of $\hat{B}_r/B \sim 3 \times 10^{-4}$ (edge) or $\sim 4 \times 10^{-5}$ ($q = 2$) is necessary to yield experimentally-deduced thermal conductivities. Results of comparisons with fluctuation level and correlation length predictions from various models indicate that drift waves, rippling modes, and "skin-depth" turbulence models are inferior candidates, and that resistive ballooning or possibly microtearing modes offer better possibilities for a consistent explanation of the data. Finally, theoretical calculations indicate that the resistive ballooning model is also consistent with good runaway confinement during H-phase.

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

FRC Tilting Stability Results with the Self-consistent Eigenfunction*

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Previous studies of kinetic stabilization of the internal tilting mode in Field-reversed Configurations (FRC's) assumed the MHD eigenfunction as a trial function.[1] Here we report on stability calculations that result from solving for the "self-consistent" tilting eigenfunction. For elongated, elliptical-like FRC's, MHD theory predicts[2] that the eigenfunction has the form $\xi(\psi,\chi,\vartheta) = e^{in\vartheta}[\xi_z(\psi)\hat{z} + \xi_\vartheta(\psi,\chi)\hat{\vartheta}]$, where ψ labels a flux surface and χ labels distance along a flux surface. Therefore, we represent

$$\xi_z(\psi;\omega) = \sum_{i=1}^{N} a_i(\omega) S_i(\psi). \qquad (1)$$

The functions $\{S_i(\psi)\}$ are unevenly spaced cubic splines, where ψ runs from $\psi = -1.0$ (O-point) to $\psi = 0.0$ (separatrix). (Since the mode is internal, we choose as a boundary condition at the separatrix that $\xi_z(0.0) = 0.0$.) The spline knots are chosen to be tightly spaced near $\psi = -1.0$, as earlier calculations with 12 evenly spaced splines suggested that the self-consistent eigenfunction peaks near the O-point.

We use representation (1) in the dispersion equation and the Galerkin procedure to obtain a matrix problem to solve for the unknown coefficients $\{a_i(\omega)\}$. The eigenfrequencies ω satisfy $\det D(\omega) = 0$, where $D(\omega)$ is the dispersion matrix. The key dimensionless parameter in our calculation is $\bar{s}$, which measures the number of local ion Larmor radii between the field null and the separatrix. For $\bar{s} = 7.0$ (MHD regime) we calculate that the self-consistent eigenfunction gives nearly the <u>same</u> reduction in growth rate relative to MHD as does the trial function. Results for other values of $\bar{s}$ will be presented.

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*Work performed under the auspices of the U.S.D.O.E.

PARAMETRIC PROCESSES IN ION CYCLOTRON HEATED PLASMAS*

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In order to study the parametric instabilities and associated plasma heating with rf waves in the ion cyclotron wave frequency range, a series of particle simulations are performed using an optimized 2-1/2 D ($x - y$, $v_x - v_y - v_z$) electromagnetic model. A circularly polarized, non-dipolar ($k_o \neq 0$) electromagnetic pump wave ($\omega \approx \omega_{ci}$) is launched into a uniform strongly magnetized plasma. For very large amplitude pump waves ($v_o \gtrsim 2v_{thi}$) the field-line averaged ion distribution forms a ring in the perpendicular velocity space which is unstable to electrostatic waves. For lower pump wave amplitude, below the threshold for unstable ion distributions, the decay instabilities are observed. The decay of the long wavelength pump into shorter perpendicular wavelength electrostatic ion cyclotron modes[1] ($k_\perp \rho_i \gtrsim 0.8$), as well as into transverse electromagnetic ion cyclotron and ion acoustic modes is found[2]. The decay process occurs mainly through nonlinear ion Landau damping. When waves with opposite phase velocities are generated, strong parallel ion cooling accompanies the perpendicular heating. The heating rate versus pump strength, as well as results for two ion species, will be presented.

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Feasibility of Gyrokinetic Particle Simulation of Tokamaks*

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The feasibility of using gyrokinetic particle simulation techniques[1] for studying problems associated with tokamak discharges has been examined. The primary concerns here are the restrictions imposed by the nonlinear gyrokinetic equations on the time step and the grid spacing for such a code. As reported earlier,[2] the electrostatic version of the code is limited by $\omega_H \Delta t \lesssim 1$ or $k_\parallel v_{te} \Delta t \lesssim 1$, whichever is more strigent, and $\Delta x_\perp / \rho_s \lesssim 1$, where $\omega_H \equiv (k_\parallel / k) \sqrt{m_i/m_e}\, \Omega_i$ and $\rho_s \equiv \sqrt{T_e/T_i}\rho_i$. There is no restriction on the size of $\Delta x_\parallel$. With the introduction of vector potential $A_\parallel$ to account for the finite-β effects, the characteristic frequency changes from ω_H to ω_A, where $\omega_A \equiv k_\parallel v_A / [1+(ck/\omega_{pe})^2]^{1/2} \equiv \omega_H / [1+(\omega_{pe}/ck)^2]^{1/2}$ is the usual shear-Alfven frequency. Since $\omega_H > \omega_A$ and $v_{te} > v_A$ for finite-β plasmas, the time step is now governed by $k_\parallel v_{te} \Delta t < 1$ only. In order to satisfy this electron transit time requirement, one can use the orbit-averaging scheme[3] by pushing N_e numbers of electrons with a time step of Δt, while pushing N_i numbers of ions and updating the field equations with a time step of ΔT prescribed by $\omega_A \Delta T \lesssim 1$, where $N_i/N_e = \Delta T/\Delta t$. By calculating the electron orbits with the fields which are constant in time and by accumulating the information on the field quantities in successive Δt's, we can achieve the same statistical accuracy with proportionally less number of electrons. Hence, the effective time step in the code is ΔT. In the presence of shear, the situation is further improved. In this case, the low-frequency normal modes associated with ω_A (and ω_*) solely determine the time step of the simulation. Another important consequence of the finite-β effects is the removal of the restriction on grid spacing. Thus, a code of this kind can be used to study the micro-behavior and, to certain extent, the macro-behavior of tokamak plasmas.

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

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NONLINEAR THEORY OF ENERGETIC TRAPPED PARTICLE-INDUCED RESISTIVE INTERCHANGE MODES*

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In recent work,[1] we have shown that energetic particles, trapped in the region of adverse curvature in tokamaks, can linearly destabilize both ideal ($\omega \simeq \bar{\omega}_{dm} \gg (n^2/S_M)^{1/3}\omega_A$, where S_M is the magnetic Reynolds number, $\bar{\omega}_{dm}$ is the hot particle precessional drift frequency, and ω_A is the Alfvén frequency) and resistive ($\omega \simeq \bar{\omega}_{dm} \lesssim (n^2/S_M)^{1/3}\omega_A$) interchange-ballooning modes when the wave structure starts to resonantly interact with the precessional drift motion of the hot particle banana centers. The linear picture having emerged, we have embarked on a nonlinear analysis with the ultimate goal of estimating the anomalous transport resulting from these energetic trapped particle-induced modes.

The core plasma behavior is described by a nonlinear set of resistive MHD equations, while the hot particle response is obtained by taking appropriate velocity moments of the nonlinear gyrokinetic equation. The system of equations takes into account convective $\mathbf{E} \times \mathbf{B}$ and ion polarization drift nonlinearities. Due to the highly localized nature of the the linear eigenmodes relative to the separation between mode rational surfaces, a single-helicity approach is appropriate. Results of detailed calculations will be presented.

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

SIMULATION OF LOWER HYBRID WAVE CURRENT RAMP-UP

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ABSTRACT

The time dependent behavior of distribution of electrons and changeing rate of current had been studied. The quasiliner code written by E. Moghaddam-Taaheri can then be used to simulate one dimension homogenous plasma been ramped-up or started up current by lower hybrid wave. Few different intinal distribution function was set in the code. Some numerical results and analytic asmptotic limints for the efficiencies are given.

IDEAL AND RESISTIVE MHD-STABLE REGIME OF THE TOKAMAK*

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In order to understand the relationship between tokamak $T_e(r)$-profiles and observed global energy confinement, Furth[1] suggested that tokamak profile consistency may be related to current profiles, J(r), that are stable to both ideal and resistive kink instabilities. In resistive equilibrium, the shape of $T_e(r)/T_e(o)$ is roughly proportional to $J(r)^{2/3}$, with the magnitude of $T_e(o)$ calibrated by some average dT_e/dr in the edge region.

The object of the present study is to determine the total range of stable J(r) profiles (with $dJ/dr \leq 0$), as q(o) and q(a) are varied. Our calculation is based on the marginal stability ($m, n \leq 20$) of an infinitesimally perturbed pressureless equilibrium[2] in a straight cylinder with no conducting shell. In terms of a comparison theorem derived in Ref. 3, we first show that there is no stable J(r)-profile of any shape for $m - 1 < nq(o) \leq nq(a) < m$. For q(o) = 1, we obtain a family of stable J(r) profiles when $q(a) \geq 2$, with J(r) becoming unique as $q(a) \rightarrow 2$. Note that the lowest q(a)-value found for any stable J(r)-profile with q(o) = 1 in previous investigations[4] was q(a) = 2.6. To illustrate how much latitude in profile shape becomes available at higher q(a), we have calculated the range of permissible internal-inductance values as a function of q(a).

For q(o) < 1, experimental tokamak plasmas are characterized by the sawtooth mechanism, which is related to the m = n = 1 resistive kink mode. Assuming that the m = n modes may prove to be controllable by special techniques,[5] we look for J(r) profiles that are stable against all the other m,n modes. Our results indicated that there can be no stability for q(o) < 0.5, due to the unstable m = 1, n = 2 modes. For q(o) = 0.5, we have found stable J(r) profiles as q(a) is lowered down to 1 — a significant improvement relative to Ref. 5.

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

STABILITY CRITERIA AND RELAXED STATES FOR DOUBLE ADIABATIC MHD

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A special class of invariants of anisotropic MHD are used to produce relaxed states, i.e., states that should exist after turbulent relaxation with reconnections and parallel heat flux. These states have uniform $T_\perp, T_\parallel$ but have gradients in density and in $\lambda \equiv \underset{\sim}{j} \cdot \underset{\sim}{B}/B^2$. This class of invariants includes two entropy functionals $S_1 = \int \rho F_1(p_\perp/\rho B) d^3x$ and $S_2 = \int \rho F_2(p_\parallel B^2/\rho^3) d^3x$, with $F_1(s_1) = \ln s_1$ and $F_2(s_2) = \ln s_2$. Second variation provides a sufficient condition for linear stability. A more general class of equilibria are formed with arbitrary F_1, F_2. These results are compared with those of the "energy-Casimir" approach to nonlinear stability.[1]

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This work was supported by the U.S. Department of Energy and by the Center for Theoretical Physics, University of Maryland.

DOE/ER/53223-12

ALPHA PARTICLE EFFECTS ON PLASMA EQUILIBRIA*

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ABSTRACT

Recent interest in an ignition experiment stimulated us returning to a problem where the effects of alpha particles was shown to be dramatic. We reported earlier[1] on a 1-1/2 D transport simulation code; this code was used in a conceptual study of a moving-ring reactor[2] where the equilibrium was shown to depend critically on the α-particle retention. The code contains the physics necessary to self-consistently follow compression and expansion with consequent changes in plasma geometry. Radiation, refueling and full reaction kinetics of the thermonuclear burn allow simulation of a burning CT plasma. We use Braginskii transport coefficients, adjusted to give reasonable agreement with present day CT experiments. We found that without refueling using cold plasma, the burn is unstable and the plasma will expand with the shape changing from spheromak-like to FRC-like. Our recent studies will show how to stabilize the burn by appropriate refueling as well as controlled impurity radiation. We will present again a description of the model, the code, recent results as well as suggestions for improvements in the model by using results from other studies.[3]

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*This work is partially supported by U.S. Department of Energy Grant No. DE-FG02-86ER53223 and by EPRI Contract No. RP-922.

SHERWOOD THEORY MEETING

Turbulent drift-wave dynamics in a sheared slab with a search for coherent structures *

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We invetigate numerically the dynamics of drift-wave turbulence in the absence of any phase-lag assumption between $\tilde{n}$ and $\tilde{\phi}$, *i. e.*, no Hasegawa-Mima equation. This allows nonlinear driving to dominate if such occurs. It is necessary to drop the usually-assumed phase relation $\tilde{n}/n_0 = (e\tilde{\phi}/T)(1 - i\delta)$ because of the presence of both adiabatic and hydrodynamic regions, *i. e.*, $\omega\nu_e \gtrless k_\|^2 V_e^2$, where we assume $k_\| = k_\|' x$. The physical behaviour is expected to be very different between the two regions. The equations used are charge conservation, electron continuity, and parallel ion momentum. These are solved in a layer thin compared to global scale lengths but including the sound wave parallel damping point. The 2D scheme is finite differenced in the gradient direction (x) and spectral in the periodic direction (y). A semi-implicit scheme is used on the $\nabla_\|^2(\tilde{n} - \tilde{\phi})$ terms to allow for comparatively large timesteps. A hyperviscosity of the form $k_y^6 k_x^2$ allows for a thin dissipation range so that relatively few modes need be kept. With this procedure we start a random-phase initial state with a prescribed spectrun and a spatial Gaussian envelope, and allow it to relax. We will show the resulting k_y-spectra as well as coherence diagnostics such as kurtosis for a variety of runs. In particular, we will compare the cases in which the adiabatic-hydrodynamic crossover point falls within or outside an ion gyroradius of the $k_\| = 0$ point. (This transition occurs for $C \equiv \omega_* \nu_e / k_\|'^2 \rho_s^2 V_e^2 = 1$.) Preliminary results indicate a convergent spectrum with a plateau at $k_y \rho_s \sim 1$, a low $\tilde{n} - \tilde{\phi}$ correlation in the hydrodynamic region, and a high kurtosis value indicating the formation of coherent structures in this same region. Besides the fact that we do not force the $\tilde{n} - \tilde{\phi}$ correlation with an $i\delta$ assumption, this work differs from previous efforts in that the latter contained no coherence diagnostics, did not contain enough k_y-modes, and probably had too much dissipation to prevent pile-up at the high end of k_y-space.

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

HIGH-SPEED PELLET FUELING OF OHTE/RFP PLASMAS: THEORY ISSUES

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Recent experiments on Alcator C and D-III have demonstrated that deep-penetration pellet fueling can peak the plasma density profile on axis in tokamaks and produce a corresponding increase in the energy confinement time[1,2]. The electron temperature profile was seen to rapidly relax on a time scale shorter than the pellet lifetime while the associated sawtooth amplitude and period was observed to increase with time. The question remains whether similar results will be observed in OHTE/RFP-type plasmas which appear to be characterized by rather flat plasma profiles at the 500 kA current level. Near-term pellet fueling experiments on ZT-40M will also hopefully address the following issues: 1) how will pellet fueling affect the cyclic plasma relaxation brought about by nonlinearly-coupled, resistive m=1 modes; 2) can pellet fueling be properly phased with F-Θ pumping cycles; 3) how much penetration is needed to efficiently fuel the plasma core; and 4) can over penetration cause pitch minimums that result in violent m=1 ideal kink modes.

A 1-D transport code coupled to a 1-D MHD stability and a 3-D MHD stability code is being used to simulate high-speed pellet fueling for OHTE/RFP plasmas. An improved neutral ablation model benchmarked by experiments on TFTR[3] will be used to estimate the pellet ablation times and penetration depths along with the radial fueling profiles.

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SHERWOOD THEORY MEETING 1986

Calculation of Fourier Coefficients on a Rational Magnetic Surface *

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A quantity on a flux surface can be adequately characterized by its Fourier coefficients, of the form $f = f_0 \left[1 + \sum_{nm} f_{nm} \exp\ i(n\varphi - m\theta)\right]$, where φ and θ are magnetic coordinates. The Fourier coefficients can be computed with integrations along the field line, replacing θ by $\iota\!\!\!-\, \varphi$, where $\iota\!\!\!-$ is the rotational transform.[1] We propose a method to study the higher order rational surfaces by evaluating the Fourier coefficients on any close magnetic surface. We will describe its implementation in different magnetic configurations.

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

The Establishment of the Electrostatic Field In a Stellarator

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ABSTRACT

A particle-in-cell transport simulation has been developed to model the evolution of electrostatic potentials in stellarators. The analysis is done by decomposing a poloidal cross-section. The code uses a rectangular grid, one axis of which corresponds to the poloidal angle and the other to the minor radius. 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". The toroidal angle corresponds to the third coordinate. An analytic vacuum stellarator field was used in the simulation to observe the evolution of the surfaces of constant electric potential. In this case, the configuration is ℓ=3, 7 field periods. The ℓ=3 nature of the surfaces is clearly evident. The surfaces are followed for the same toroidal angle and thus the vertical deflection is a measure of the rotational transform, which is seen to monotonically increase, and has a value of .6 at the outside edge. The surfaces are seen to be similar, but not identical, to the magnetic surfaces.

This work is supported by the U.S. Department of Energy Grant No. DE-FG02-86ER53216.A000 and Oak Ridge National Laboratory Contract No. 19X-27434C.

1986 SHERWOOD THEORY CONFERENCE

ON THE VELOCITY-SPACE STRUCTURE OF RUNAWAY ELECTRONS

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The region of velocity space is determined in which electron runaway occurs due to a dc electric field. Phase-space analysis of the relaxation equations describing test electrons, corroborated by 2-D numerical integration of the Fokker-Planck equation, reveals that the Dreicer condition for runaway $v_\parallel^2 \geq (2+Z_i)\, E_c/E$ is only sufficient. We establish a weaker condition $v_\parallel^2 \geq (2+Z_i)^{\frac{1}{2}}\, E_c/E$, and, in general, that runaway in velocity-space only occurs for those electrons which are outside one of the separatrices of the relaxation equations. We also derive the scaling with $v_\parallel$ of the parallel distribution function and of the perpendicular temperature.

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STATIONARY RESISTIVE EQUILIBRIA IN TOKAMAKS

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ABSTRACT

In a stationary tokamak, in which the current is induced by induction, the current profile is determined, through the Spitzer resistivity, by the temperature profile and the pressure profile is determined by the temperature and density profiles. The stationary state is then maintained by sources and sinks of particles within the plasma. We propose an algorithm for constructing such stationary equilibria, given the density and temperature profiles, and present examples of the equilibria obtained from this procedure, together with an analysis of their stability properties.

We find that the density profile has very little effect on the stability to n = 1 kink modes, but that the stability is strongly dependent on the temperature. The β limits obtained from a limited optimization over the temperature profile in a circular cross-section tokamak with aspect ratio 5, are found to lie at about 70% β_T, where $\beta_T = 2.2(\mu_0 I/R_0 B_0)A$. For a tokamak with JET parameters and cross-section, we have investigated the stability of density and temperature profiles obtained from experimental data and the results of this study will also be discussed.

CURRENT AND β LIMITATIONS IN TOKAMAKS

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ABSTRACT

Recent β optimization studies have indicated the existence of a β limit proportional to the plasma current and this has been corroborated by experimental evidence of a similar operational β limit. Nevertheless, the underlying physics is not yet clear.

A study of the stability of circular cross-section plasmas to n = 1 kink and large n ballooning modes, using the ERATO stability code, is presented in an effort to clarify the situation. Low β stability to current-driven modes is analyzed and the results summarized on an operational diagram in the (q_{min}, q_{surf}) plane. This permits the classification of current-driven instabilities as well as the determination of the corresponding stability criteria.

An optimization procedure is used to optimize the β at any given current, by optimizing against kink and ballooning modes within the stable region of the low β operational diagram. With the optimization procedure used, significant deviations from the linear scaling with current are found and these will be discussed.

NUMERICAL SOLUTIONS FOR A CIT DIVERTOR MODEL*

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A poloidal divertor option is being considered for the US Compact Ignition Tokamak (CIT). The small aspect ratio, combined with a high power, creates conditions not encountered before in either the existing or projected experiments. These conditions result in unusually large pressures, and therefore very high densities in the scrape-off model. Since the maxiumum scrape-off electron densities are a function of the unknown radial particle transport coefficients on the separatrix, the maximum permissible density cannot be determined accurately. Using the steady-state plasma transport code (PLANET) and the neutral transport code (DEGAS), we present results for scrape-off plasma densities and temperatures for a variety of different boundary conditions.

*Supported by the U.S. DOE Contract No. DE-AC02-76-CHO-3073.

ELECTRON CYCLOTRON WHISTLER MODE EXCITATION AND APPLICATION IN A TOKAMAK*

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The coupling into the whistler wave branch of the electron cyclotron (EC) wave is investigated for tokamak geometry. It is demonstrated that the X-mode inside launch of the EC wave can be used conveniently for high density tokamak discharges to couple into the whistler wave branch. The mode conversion processes are being examined.

The application of such whistler excitation of the EC wave may be important for localized current drive. This is a consequence of the fact that the energy transfer between the whistler EC wave and the plasma can be maximized around the localized O-mode cutoff density. Examples of the process applied to the PLT tokamak will be presented.

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

MHD SIMULATION OF COLUMBIA HBT FOR 2nd STABLE REGIME EQULIBRIA

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It is our intention to simulate the formation of the 2nd-stable regime equlibria of Columbia HBT by external current drive. We have improved H. Liu's two-dimensional MHD inital value code/1/ by making the boundary condition for the poloidal flux self-consistent. An intensive study has been done for different external current drives during and after the toroidal field reversal phase (the toroidal field is reversed to induce poloidal currents in order to heat the plasma to the high beta state). The simulation results have been compared with experiment and are found to be in good agreement. The PPPL equilibrium and stability code (PEST) and the balloning mode stability code (BALLON) are used to search for equilibrium states that are in the second stable regime for Columbia HBT. Finally, the inital value code is used to program the external current drive to reach the high beta equilibrium state we get from the PPPL equilibrium and stability codes.

* Work supported by US DOE grant DE-FG02-86ER53222

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NONLINEAR REDUCED MHD EQUATIONS WITH MAGNETIC PUMPING IN TOROIDAL PLASMAS

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Cross field motion of plasma during the nonlinear growth of MHD instabilities in tokamaks causes compression of the local tubes of flux. The resulting magnetic pumping dissipates the plasma motion. A set of simple 2-D nonlinear helical MHD equations are derived which describe this process in a large-aspect-ratio, low β tokamak. The calculation is carried out by transforming to a helical coordinate system and performing a two-space-scale analysis in which the toroidal periodicity is averaged. The resulting equations are similar to the cylindrical helical reduced equations obtained previously[1] but include an evolution equation for the parallel flow $v_\parallel$. In the axisymmetric limit, poloidal flows are damped at a rate of order $\nu_{ii}\ell_i^2/q^2R^2$, where ν_{ii} is the ion collision frequency, ℓ_i is the ion mean-free path, and qR is the tokamak connection length.[2] Toroidal flows remain undamped. The damping does not affect the stability of the tearing mode, but the effective inertia of the plasma increases by a factor $(R/a)^2$ due to the large parallel flows $v_\parallel \sim (R/a)v_\perp$.[3,4] These equations are being incorporated into a 2-D MHD code to study the effects of magnetic pumping in sawteeth and other MHD activity.

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

Equilibria in Ellipsoidal Coordinate System

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The Grad-Shafranov equation for axisymmetric plasma equilibria has been solved in the ellipsoidal coordinate system (ρ, ς, ϕ) with constant current density profile up to the sixth order in ς. Bean shaped equilibria are describable in this coordinate system. The basic characteristics of these equilibria are determined by the size, aspect ratio, elongation, poloidal beta, triangularity, and separatrix location.

Effect of Large-Amplitude Perpendicularly-Propagating RF Waves on the Interchange Instability

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Results are presented from hybrid 2-d quasineutral Darwin simulations of the interchange instability in the presence of a large RF wave in the ion-cyclotron frequency range. The simulation models the plane perpendicular to the background magnetic field using cold, particle ions and a cold $\mathbf{E} \times \mathbf{B}$ electron fluid. Related theory is also discussed. Fluid equations appropriate to our simulation model are derived and their properties demonstrated and compared to simulation. A method for solving for the RF-modified growth rates from the fluid equations is described. It is generally expected that the current component associated with the mean, RF-induced ion drift is capable of influencing the stability of the interchange mode; however, no modification of the mean ion drift is observed in simulations in which RF is present. Instead, in both the theory and simulation, an electron RF-field oscillation current dominates the modification to the gravitational current. As a result, even in the presence of large RF fields, ($B_{RF}/B_0 = 15\%$) only modest corrections to the interchange growth rates are observed. The effect is stabilizing for $kL_n \lesssim 0.8$–0.9, apparently for both signs of the square-electric-field gradient, and is destabilizing for larger values of kL_n, where numerical instabilities may be present. Fractional reduction of the interchange growth rate was observed to be quadratically dependent on the RF wave amplitude, independent of ion-cyclotron resonant effects, and proportional to $\nabla B_{RF}^2/\nabla B_0^2$, consistent with an eikonal theory developed for the study of stabilizing effects on perpendicularly-propagating fast Alfvén waves. The results also suggest that additional gradient-independent stabilizing effects may be operative when $kL_n \sim 1$. Finally, it is also observed that, while the RF wave has little effect on the interchange instability, the interchange mode strongly affects the RF wave, damping it significantly as the mode saturates.

DOE/ER/53223-8

3D TRANSPORT SIMULATION I: CODE AND VARIATIONS*

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ABSTRACT

This series of presentations continues work in fully 3D simulation transport codes (3D-ETC) for which initial results were described in "Ripple Penetration..." by Ibanez, Bayliss, Grad, 1983 Sherwood Meeting. The Alternating Dimension algorithm is used to solve 3D classical transport with Braginskii coefficients. The code is very modular and allows an essentially plug-in equilibrium solver. There is no approximation introduced by 1D averaging; this is a mathematical tool for efficient iterative solution of the pointwise 3D plasma equations. The configuration is shaped by an outer shell which can touch the plasma or is separated from it by a vacuum or cool plasma; a limiter can be placed in the vacuum; at present the equilibrium solvers do not allow divertors in 3D; islands are estimated. External constraints can be any two of the following, programmed in time: vacuum fluxes or mmfs plasma volume, toroidal plasma flux or current, q at plasma edge, loop voltage. Neutral injection sources and impurity radiation are included. An assortment of plasma-vacuum interface boundary conditions can be accommodated, also explicit or implicit 1D marching. For all physical tokamak configurations, the 3D equilibrium has to be updated at most two or three times to cover approach to equilibrium (many minutes -- longer than any proposed experimental pulse time), even though the 1D evolution time steps (cheap) are measured in thousands.

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*This work is partially supported by U.S. Department of Energy Grant No. DE-FG02-86ER53223.

**Exxon Corp.

***EBASCO, Inc.

Calculations of Electron Distributions for Thermal-Barrier Tandem Mirrors*

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We present results of a series of calculations for the evolution of both central-cell and end-cell electron distributions in a thermal-barrier tandem mirror configuration. The calculations are performed using the multi-region Fokker-Planck code SMOKE and the Monte Carlo code MCPAT. The power input is electron cyclotron resonance heating (ECRH) in the end cell. The potential profile is specified; parameters are chosen to be in the range of the TMX-U experiment. Conclusions of the study are as follows: (1) The second harmonic ECRH diffusion ($\omega = 2\omega_{ce}$) determines the ratio between the central-cell and end-cell densities; (2) Strong fundamental ECRH diffusion drives enhanced end loss, and can also produce an end-cell electron distribution which yields negative power absorption of the second harmonic; (3) A small amount of fundamental ECRH ($1 \sim 5$ KW) is required to produce the ion-plugging potential in the end cell; and (4) Substantial central-cell electron heating from passing electrons occurs only for $\phi_{sb}/T_{ec} \lesssim 3$, where ϕ_{sb} is the central cell to end-cell barrier potential and T_{ec} is the central-cell bulk electron temperature. However, for $\phi_{sb}/T_{ec} \lesssim 3$, the end-cell density becomes several times the central-cell density. These results are compared with those from a theoretical model described in an adjacent paper.

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* Work performed for U.S.D.O.E. by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

Modelling of ECRH-heated Electrons in Tandem-Mirror Thermal Barriers*

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A set of models for electron-cyclotron resonance heated (ECRH) electrons in a thermal barrier cell of a tandem mirror has been developed. Magnetically trapped barrier electrons are considered as the sum of a Maxwellian at the center-cell electron temperature plus a distribution which is constant along second-harmonic heating characteristics. Electrons passing from the center cell are treated by interpolation between collisional and strong fundamental-heating limits. In the collisional limit, the passing electron distribution is nearly Maxwellian (but falls to zero at the loss boundary). In the strong-heating limit, the passing and magnetically trapped distributions are determined by flux conservation and collisional scattering betweeen heating characteristics. The potential-trapped plug electrons are also treated by interpolation between collisional and strong-heating models, as described previously.[1]

These models have been incorporated in TREQ,[2] a multi-species coupled point-model rate package for thermal-barrier tandem mirrors which is part of the MERTH omnibus tandem-mirror code. TREQ simultaneously solves rate equations and constraint equations describing particle, energy and charge balance to self-consistently determine densities, energies and potentials at cardinal points. TREQ has been exercised to explore the parametric dependences of the model and to map out the limits of end plugging for TMX-Upgrade parameters. The results are in general agreement with the behavior observed in TMX-U.

A prediction of the models is that, in the limit of a strongly heated short plug region and a weakly heated long thermal-barrier region, the distribution of potential-trapped electrons is inverted as a function of parallel velocity; this manifests itself in TREQ through multiple roots for the plugging potential, but physically would lead to an electron two-stream instability. Modifying the model for potential-trapped electrons to render them at least marginally stable restores single-valuedness to the potential solution but leads to a plugging potential which can change rather abruptly as a function of parameters or time, much as observed experimentally during loss of plugging.

* 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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Fast Wave Coupling to Ion-Bernstein Wave in Tokamak Edge Plasma During ICRF Heating,* S.N. ANTANI and J.E. SCHARER, Electrical and Computer Engineering Department, University of Wisconsin, Madison, Wisconsin 53706

Recently Skiff et al.[1] have reported observations of parasitic excitation of ion-Bernstein wave (IBW) from a fast wave antenna in the frequency range $\Omega_i < \omega < 2\,\Omega_i$. This was interpreted as being due to the action of the edge density gradient on the incident fast wave. In this paper a quantitative study of this process is carried out. The analysis is based on a model analogous to that described by Morales et al.[2] in which the IBW is considered to be excited by a known source term arising from the properties of the fast wave and the plasma gradients. The source term is calculated using the fast wave description of Ram and Bers.[3] For a parabolic density profile, the evaluation of the source term indicates that the coupling would be significant only close to the fast wave cut-off. Using the expressions for the hot, non-uniform plasma dielectric tensor elements (operators), an inhomogeneous differential equation for the excited IBW is obtained. This equation will be considered in some interesting limits and the results will be evaluated for parameters of ACT-1 as well as large tokamaks such as JET.

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*Research supported by DOE Contracts DE-AC02-80ER53104 Task III and DE-AC02-83ER52090.

SPHEROMAK TILT STABILIZATION WITH PARTICLE RINGS

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A survey is made of compact toroid equilibria with an energetic particle ring component. An alternative to the full MHD-Vlasov stability analysis has been developed for obtaining necessary upper limits on the fast-particle current required for tilt stabilization of the spheromak plasma. The magnetic energy, W_m, of the full system is expressed in terms of the calculated equilibrium fields of each component. The condition for tilt or shift stability is that the corresponding force, $F_\alpha = \partial W_m/\partial q_\alpha$, be opposite to the rigid displacement, $\delta q_\alpha = \delta\theta, \delta x, \delta z$. The results of the survey indicate that tilt-stable equilibria exist with $\lesssim$25% of the total toroidal current in the fast particle ring.

CONFINEMENT ANALYSIS OF COMPACT IGNITION TOKAMAK (CIT)*

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A comprehensive confinement study has been carried out for compact ignition tokamak (CIT) experiments to assess confinement, heating and fueling requirements, and fast alpha particle effects (slowing down, diffusion, and the degree to which core plasma confinement depends on alpha power). The confinement scalings considered range from an optimistic model based on ohmically heated plasmas to pessimistic models (L-mode scalings) that include confinement degradation by both auxiliary and alpha heating. Favorable H-mode confinement seen in tightly closed divertor geometries is also considered. For a wide range of confinement models, the "figure-of-merit" parameter aB_0^2/q_{cyl} (or equivalently B_0I) is found to give a good indication of relative performance of the devices.

Considering conservative density ($\langle n_{20}\rangle_{max} \approx 1.5\ B_0/q_{cyl}R_0$) and beta ($\beta_{crit} \approx 3\ I/aB_0$ %) limits and assuming confinement degradation with alpha power, the results of the study show that a class of CIT devices with $aB_0^2/q_{cyl} \sim 25$-30 ($B_0I \sim 100$-120), $\kappa \sim 1.8$, and $A = R_0/a \sim 2.8 \pm 0.2$ (corresponding to a set of device parameters $a \sim 0.4$-0.5 m, $R_0 \sim 1.1$-1.4 m, $B_0 \sim 10$-11 T, $I \sim 10$-11 MA) should be ignitable with a finite ignition window (ignition margin $M \geq 1$) under modestly conservative L-mode confinement scalings (such as Kaye-Goldston). A small ignition window restricts the alpha particle physics studies. Under more pessimistic scalings, or with more stringent operational limits on $\langle n\rangle_{max}$ and β_{crit}, $Q \sim 10$ operating space should be accessible with modest auxiliary power ($P_{aux} \sim 10$-15 MW). However, under more optimistic confinement (i.e., H-mode, or no degradation due to alpha power, or sufficiently relaxed operational limits) a large ignition margin ($M \geq 1.5$) can be realized, which opens up a broader range of alpha particle physics.

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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.

Toroidal Divertor Tokamak*

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A plasma confinement configuration of current carrying toroidal plasma with toroidal divertors is proposed. The magnetic neutral X-point forms a ring in the toroidal divertor, which helps the rotation of field lines in the poloidal direction and formation of a deep magnetic well at the separatrix. In this concept, the core plasma is confined by the toroidal plasma current as usual in a tokamak, while the edge plasma is confined by the magnetic well at the separatrix as in Pluton[1] and STE.[2] The local rotational transform of magnetic field lines and magnetic well in the toroidal divertor are calculated in a cylindrical model. The rotational transform sharply increases near the separatrix, which induces a large shear and significant reduction of the local safety factor. Stabilization of low (m, n) current driven kink and tearing modes by the line tying effect in the toroidal divertor and plasma transports induced by magnetic ripples are discussed, where m and n are the poloidal and toroidal mode number, respectively. Advantages of the present concept, *e.g.,* major disruption control, relaxed ignition condition, purification of core plasma, and possibility of steady state operation, are also suggested.

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Turbulent MHD Transport Coefficients: A New Approach

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ABSTRACT

(for the Sherwood Theory Meeting in New York, 1986)

A new analytical approximation method, which had been developed to obtain the Kolmogorov energy spectrum distribution in the inertial wave number range in incompressible homogeneous turbulence, has been extented and applied to the incompressible MHD turbulence case. In this method, a new eddy-viscosity assumption is introduced which has different form from that in Heisenberg's semiempirical theory as well as in the "DIA". Using our method, we have derived new analytical expressions for the MHD turbulent amplification rates for the large scale mean fields due to the small scale fluctuations. The so called "alpha dynamo" effect and "beta dynamo" effect expressions are obtained as perturbation-theory limits, and are similar to, but not the same as those gotten by Moffatt et al. The transport coefficients and spectra obey coupled integral equations. The two effects, originally introduced in the theory of space-physics dynamos, may form a possible tool for explaining field-reversal sustainment phenomena in reversed field pinch experiments.

Enhancing Fusion Reactor Efficiency by Breaking Reaction Product Adiabaticity In Advanced Fuel Tandem Mirrors

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Fusion reactor net efficiencies of at least 65% are shown to be feasible through a new mode of advanced fuel tandem mirror operation. End loss for those fusion products not needed to sustain the plasma against losses would be enhanced by induced nonadiabaticity. Since the loss time for nonadiabatic fusion products is much shorter than their energy transfer time, this leads to a narrow end loss energy spectrum and resultant very high efficiency direct electrostatic conversion.

The possibility of direct conversion has long been recognized as a benefit of open magnetic confinement systems. Previous work has investigated the efficiencies attainable by direct conversion of escaping electrons, fuel ions, and thermalized charged fusion direct convertor products. Due to the thermal spread of the escaping particles, realistic efficiencies are limited to about 65%. This poster will discuss the benefits of enhancing the scattering rate of a class of fusion products, leading to almost immediate end loss for that part of the fusion product energy not required to sustain the plasma. The resulting, narrow energy distribution of the end loss fusion products can give very high direct convertor efficiency (> 90%).

The geometry under discussion is that of the thermal barrier tandem mirror. The new operating mode has major implications for plasma power balance, but does not alter the essential thermal barrier tandem mirror configuration. The d-^{3}He fuel cycle most obviously shows the advantages of this mode of operation, and this poster will concentrate on that cycle, although the equations will be written in general form. The magnetic field gradients required to produce fusion product nonadiabaticity are estimated and shown to be well within technological limits. An approximate power balance is calculated and a reference case is given.

There are a variety of engineering questions to be resolved, including direct convertor design and ^{3}He resources, but these will be left to a future paper. It is, however, worth pointing out that there are sufficient ^{3}He resources today to fuel fusion reactors for specialized applications, such as a physics demonstration device or space.

Research supported by the Grainger Foundation, the Wisconsin Electric Utilities Research Foundation, and the US Dept of Energy, contracts DE-FG02-86ER52128 and DE-FG02-86ER53218.

SHERWOOD THEORY MEETING 1986

Resistive Ballooning Stability with Highly Energetic Particles*

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It is known that highly energetic particles—such as alpha particles, neutral-beam-injected ions, or cyclotron-wave-heated electrons or ions—could nonresonantly enhance the stability of ideal ballooning modes,[1] whereas moderately energetic particles can lead to wave-particle resonant destabilization at their curvature drift frequency.[2,3] Recently, the behavior of the resistive interchange-ballooning mode in the presence of moderately energetic, resonant particles was examined by Biglari and Chen[4] with the restriction of low beta for the hot species.

Here we investigate the effect of highly energetic (i.e., non-resonant) particles with finite beta on the stability of resistive ballooning modes. Analytically, the ideal MHD solution is matched asymptotically, by means of an exactly known Mercier-type form, to the solution for the resistive layer, with hot particles in both regions. In the limit of finite beta, finite shear, but deeply trapped hot particles, for example, we derive a dispersion relation for the complex frequency of the resistive ballooning modes, as a function of the usual Δ' quantity. With zero resistivity, this dispersion relation reduces to the results of Ref. 1. The parameter Δ' is obtained by numerically solving the ideal ballooning equation and then extracting the ratio of the non-oscillatory "small" and "large" components. An analytic expression for Δ' may also be derived in a low beta limit. The critical value of Δ' for marginal stability increases due to the energetic particles, as well as due to average favorable curvature. The stability results obtained by these analytic and semi-analytic procedures can be compared with fully numerical solutions of the resistive ballooning equations.

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

Trapped Particle Modes in the Presence of Radiofrequency Waves*

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High power rf injection is being considered as a main source for heating magnetically confined plasmas and is apparently a likely candidate for possible steady-state current drive. In hot plasmas of thermonuclear interest, the existence of magnetically trapped particles plays a major role in the dynamics of such plasmas. In this paper, we study the effect of rf waves on the dynamics of trapped particles, with particular emphasis on low-frequency trapped particle modes and modes due to energetic particles (*e.g.,* neutral-beam driven modes). The effect of such rf waves on the quasilinear modification of the distribution function and possible modification of the drift-orbits will be studied. The resulting effect of such modification on the linear growth rates will also be presented.

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

Abstract for 1986 Controlled Fusion Theory Conference

One-Dimensional Modelling of DC Current Drive by AC Helicity Injection in a Tokamak

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A one-dimensional model has been developed to study the mode-beating interpretation [P.M. Bellan, Phys. Rev. Lett. 54, p. 1381 (1985)] of dc current drive by ac helicity injection in a tokamak. It was hypothesized that a dc toroidal current might result directly from the nonlinear beating of two normal modes of the tokamak plasma driven by oscillations of the toroidal and poloidal magnetic field circuits; no magnetic reconnection or relaxation was invoked. The resulting dc poloidal magnetic field field was predicted to be comparable or larger than the driving ac poloidal field for small modulations of the toroidal field. However, results from the one-dimensional (radial variation only) resistive MHD slab model presented here show that no significant dc toroidal current drive results from this process when the effect of the radial motion of the plasma boundary, caused by the oscillation of the toroidal field, is properly included. This negative result is interpreted in terms of Faraday's law, which shows that, for any axisymmetric toroidal plasma described by the resistive MHD plasma equations with variation in the minor radius direction only, no dc poloidal field comparable to the driving oscillatory poloidal field results from the mode beating process. Whether or not other effects, such as magnetic reconnection, a non-local ohm's law, or nonconservation of plasma, could lead to a significant dc current drive remains an open question.

SHERWOOD THEORY MEETING 1986

Simulation Study of Nonlinear Ohm's Law *

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The longitudinal Ohm's law is studied theoretically under conditions of strong nonlinearity. At high levels of fluctuations such that $\tilde{v}_\perp > v_F$, where $\tilde{v}_\perp$ is the drift velocity of the particles and $v_F = \omega/k_\perp$ is the perpendicular phase velocity, particles can become trapped in the wave troughs and this changes the parallel Ohm's law in a crucial way.

Our numerical investigations are made in the context of the shearless density-gradient-driven-drift instability. We use a standard $2\frac{1}{2}$-D electrostatic particle code with guiding center electrons and full dynamic ions. Three regimes are studied: one where the drift waves are stable, one with mild instability and a strongly nonlinear case. Detailed electron orbits diagnostics reveal a large number of particles with parallel velocity $v_\parallel \lesssim v_{Te}$, the thermal velocity, trapped by the large amplitude drift waves. Detailed time and space diagnostics of parallel current and parallel electric field reveal the expected change of character in Ohm's law upon particle trapping at high fluctuation levels. More quantitative comparisons with theory are in progress.

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

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Effect on Tearing Modes of Different Formulations of the Incompressibility Condition*

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The resistive MHD equations can be formulated in such a way that the continuity equation, which may be taken to give the time evolution of the density, can be satisfied without explicitly evaluating it. If the density is taken to be time independent, the continuity equation is

$$\underset{\sim}{\nabla} \cdot (\rho_m \underset{\sim}{v}) = 0 \ ,$$

with ρ_m the mass density and $\underset{\sim}{v}$ the velocity. Various assumptions may be made for the spacial dependence of ρ_m. The effect of these differing assumptions has been studied for tokamak $m = 1$ tearing modes using the full MHD equations without ordering assumptions. For ρ_m = const., the conventional incompressible assumption, linear growth rates are found which are smaller (more stable) than those found when a sometimes more desirable $\rho_m = R^{-2}$ dependence is assumed. The effect of various assumptions on the linear and nonlinear behavior of tearing modes will be discussed.

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

A Relativistic Fokker-Planck Algorithm for Computing ECRH in Tokamaks*

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A relativistic theory for electron cyclotron resonant heating in a Tokamak configuration is developed. The gyro- and bounce-averaged relativistic Fokker-Planck equation is presented. The relativistic Fokker-Planck collision operator is derived by generalizing the nonrelativistic Fokker-Planck operator to include effects to order β^4 in all pitch angle moments in the Legendre expansion of the distribution functions. The relativistic quasilinear operator is presented and relativistic quasilinear characteristics and resonance curves are shown. Results are compared to the nonrelativistic case.

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

3D TRANSPORT SIMULATION II: APPLICATIONS*

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ABSTRACT

To calibrate standard reference runs it is necessary to create initial equilibria which are "skinless" (e.g., to avoid interference with ripple diffusion near the edge, or to introduce measured amounts of initial skin current which is generally present in arbitrary adiabatic equilibria). Also for calibration, long runs to self-consistent transport steady state are needed for quantitative measure of relaxation times (such runs are much longer than long pulse tokamak experiments).

The re-calculation of an initial surface current as a "skin effect" layer, together with its interference with edge impurity radiation is examined to be able to identify it experimentally. The entirely independent resolution of an initial pressure discontinuity (linearly governed by a different transport eigenvalue than the skin effect) also requires identification. The nonlinear interference of ripple diffusion with other effects, including self-consistent self-interference with non-vacuum ripple has not been analytically estimated. The FCT effect of a sudden increase in β is calculated in full 3D. To be able to interpret experimental measurements of energy confinement time, it is necessary to compare global, nonlinear equilibration time (as a function of parameters) with relaxation times of local energy perturbations at various locations, magnitudes, varying β, profiles, etc. [cf. companion paper, Kress and Grad].

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*This work is partially supported by U.S. Department of Energy Grant No. DE-FG02-86ER53223.

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THE ALFVEN EFFECT RECONSIDERED: EFFECTS OF RECONNECTION AND HIGH VISCOSITY ON THE SPECTRUM OF MHD FLUCTUATIONS - W. H. MATTHAEUS, Bartol Research Foundation, U. of Delaware, Newark, DE. -- Based on an argument known as the Alfven-effect, it is commonly asserted that incompressible MHD turbulence leads to equipartition of magnetic and fluid kinetic energy at small spatial scales.[1] It is difficult to experimentally test this conjecture in many laboratory and astrophysical plasmas, so it is of interest to uncover circumstances that may lead to significant departures from equipartition. Two effects that might lead to departures from equipartition are magnetic reconnection and a magnetic Prandtl number (viscosity/resistivity) much greater than unity, both of which may be relevant to certain magnetic confinement devices. The production of coherent structures during reconnection activity favors greater magnetic energy at high wavenumbers.[2] Similarly, high Prandtl number may suppress small scale velocity structures, while fine-scale magnetic structures can still be produced. Computer simulations of MHD turbulence in two dimensions have demonstrated that both these effects lead to an excess of magnetic energy at small scales, with the Prandtl number effect being much stronger. (This research is supported in part by USDOE grant DE-FG02-85ER53194, NASA grant NAG-W710 and NSF grant ATM-8408449).

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2A-1

LATTICE GAS HYDRODYNAMICS

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THEORY AND OPERATION OF THE m=1 HELICITY SOURCE EXPERIMENT*

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The m=1 helicity source represents a method for formation and sustainment of spheromak plasma configurations that is distinct from the magnetized coaxial sources used in other spheromak experiments at Los Alamos. Its chief feature is the use of a Z-pinch discharge to inject magnetic helicity into the spheromak through a cylindrical entrance region containing no net magnetic flux. According to the principle of minimization of magnetic energy for given magnetic helicity, an m=1 helically symmetric equilibrium is expected in this region. In the flux conserver, however, the usual axisymmetric (m=0) configuration with nested toroidal surfaces is expected. Numerical computations of this hybrid three-dimensional equilibrium will be described, and puncture plots which show how the magnetic fields and flux surfaces connect in the transition region will be presented.

Observations of the m=1 structure from magnetic probe arrays will also be presented as well as data that show the configuration of plasma currents and magnetic fields throughout the entire system.

*Work performed under the auspices of the USDOE.

SEMI-IMPLICIT MAGNETOHYDRODYNAMIC CALCULATIONS*

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In many applications it is desirable to integrate the time-dependent three-dimensional, resistive MHD equations for times far in excess of a characteristic Alfvén transit time. Examples are: the growth and saturation of resistive instabilities; the tokamak major disruption; self-reversal, sustainment, and dynamo action in the RFP; and, low frequency current drive. Accurate numerical simulation, required for an understanding of these dynamical phenomena, presents a challenging problem.

Previous attempts to solve these problems have led to the development of computer codes employing explicit, implicit, and partially implicit numerical methods, as well as to reduced models. None of these attempts has been entirely satisfactory; they may require excessive computer time due to linear (explicit) or nonlinear (partially implicit) time step reduction or algorithm complexity (fully implicit), or are of limited applicability (reduced models). Recently a new class of methods was introduced to remove the fast Alfvén wave CFL time step restriction [1,2]. These were later extended to remove the shear Alfvén restriction as well [3]. In these semi-implicit method, a linear term proportional to the time step is added to the momentum equation. Proper implicit treatment of this term results in a simple consistent algorithm that is unconditionally stable with respect to normal modes, and yet requires approximately the same computation time per time step as explicit methods. The time step is, of course, still limited by advection, as is the case in all except fully implicit methods.

During the past year computer codes based on the semi-implicit algorithm have come to maturity. In this paper we present a detailed discussion of the algorithm, including a general analysis of its accuracy and stability, along with computational examples that illustrate these properties. Two different forms of the semi-implicit term are presented and compared. We also present examples of the long-time, nonlinear simulation of reversed-field pinches (RFP), field-reversed configurations (FRC), tokamaks, and the solar atmosphere. These calculations serve to demonstrate the power and versatility of the method.

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*Work performed under contracts DE-AC03-83ER53150/5 and DE-AC03-85ER53197 with the U.S. DOE, and contract NASW-4133 with NASA.

A FLUID THEORY OF PLASMA CURRENTS INDUCED BY WAVES

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Plasma currents induced by radio-frequency (RF) waves have been studied intensively because of the possibility of maintaining a steady-state toroidal current in tokamaks. Current generation has been attributed either to the absorption of parallel momentum from RF waves, or to the creation of an asymmetric plasma resistivity, or both. To obtain a unified description for these two qualitatively different mechanisms, we develop a fluid theory of plasma currents induced by waves. In the theory, the part of the particle distribution function that is responsible for the current generation is expanded in terms of a set of polynomials with physical quantities such as parallel mass flow $u_{\|}$ and heat flow $q_{\|}$ as their coefficients. These unknown coefficients are then determined from the parallel momentum and heat flux balance equations. The currents induced by lower hybrid waves and electron cyclotron waves are calculated to illustrate the theory. The results are in good agreement with previous numerical calculations. Furthermore, the theory indicates that either momentum or heat flux inputs to the plasma can generate currents. Specifically, the current driven by electron cyclotron waves, which has been attributed to the creation of an asymmetric plasma resistivity, can also be explained by the absorption of the parallel component of the heat flux induced by the waves.

*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.

PROGRESS ON THE THEORY OF FIELD-REVERSED CONFIGURATIONS AND COMPARISON WITH EXPERIMENTS

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Field-Reversed Configurations (FRC) belong to the family of toroidal confinement systems. Their plasma physics attributes are distinct from other toroidal systems in several ways. The usual FRC shape is highly prolate (elongated). FRCs have no appreciable toroidal magnetic field, and therefore have no shear, high β, and strong kinetic effects. Present day FRCs also have relatively high drift parameters. The most unique features also make the FRC attractive as a reactor concept: intrinsically high beta, and no coils linking the toroid (hence the common designation "compact toroid").

FRCs trace their lineage from early theta pinches, however, their potential as a confinement concept was appreciated only after experiments in Germany and the Soviet Union in the early 1970s. In the last several years, remarkable advances have been made, including the control of the rotational instability. These gave the impetus for the recent decision by the Department of Energy to build the LSX facility. It will be the largest FRC device in the world, and will address important stability and transport issues.

The progress of the FRC concept has benefited from a hand-in-hand connection between theory and ongoing experiments. FRCs are customarily formed in field-reversed theta pinches: global features as well as fine details of the highly dynamical formation process have been treated using analytic models and multidimensional MHD computations. These studies have facilitated the development of improved formation methodologies in experiments. Since FRCs are prolate, simplified descriptions of their equilibria have been found, and Grad-Shafranov computations made. Nevertheless certain features of the equilibria, both MHD and kinetic, remain unclear. The most important stability problem is the tilting mode. The tilt, which is MHD unstable, is strongly influenced by kinetic effects, and a Vlasov representation is presently under study. The transport of particles and energy and the decay of poloidal flux in FRCs is well known to be anomalous. This had been attributed to lower-hybrid-drift (LHD) turbulence, but extensive comparisons between experiment and LHD theory strongly suggest that some other, as yet unknown, mechanism is responsible.

Although FRC research is at a relatively early stage, its promise as a fusion confinement configuration and its unique attributes make it a particularly interesting topic for theoretical research. Several important problems are awaiting study including 3D effects on equilibrium and stability (e.g. the nonlinear development of the tilt mode); electrostatic potentials (especially in the plasma layer outside the separatrix); the low frequency stability and its effect on transport; and alternative formation techniques. These problems are of central importance to the forthcoming LSX experiment.

SHERWOOD THEORY MEETING 1986

Vortex States in Inhomogeneous Rotating Plasma*

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We present new dipolar vortex solutions of the finite beta, inhomogeneous, rotating plasma dynamical equations. The solutions describe local, shielded, polarized plasma states propagating along the magnetic surface with scalar and vector potentials of the form $\varphi(x, y + \alpha z - ut)$ and $A_{\|}(x, y + \alpha z - ut)$. This finite amplitude bounded plasma state is produced by the Poisson bracket nonlinearities arising from $\mathbf{E}_{\perp} \times \mathbf{B}_0 \cdot \nabla$ convection and $\delta\mathbf{B}_{\perp} \cdot \nabla$ magnetic field line bending. We show that previous electromagnetic (EM) vortices given by adopting the Rossby or drift-wave vortex to the EM problem produce sheet currents at the transition radius r_0. Our new solution of the fourth order EM equation yields a dipolar vortex with continuous $\delta\mathbf{B}_{\perp}$ and distributed $\delta j_{\|}$.

The dynamical equations are solved numerically for monopolar and dipolar ES drift wave vortices. Vortex collisions are studied and found to be inelastic leaving wakes of drift waves. For rotating plasma a preference for propagation in the direction of rotation is shown at low vortex energies. The relation of our studies to experiments with shallow rotating fluids is discussed. We compare our results with those of the Soviet, German, and Japanese groups.

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

SOME PROPERTIES OF MHS TOROIDAL EQUILIBRIA AND NON-EXISTENCE OF THE ISODYNAMIC STELLARATOR

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European Economic Communities

We show that, if in a MHS toroidal equilibrium the magnetic surfaces (MS) are axisymmetric and coaxial, then the poloidal and toroidal components of the magnetic field have the same symmetry and, hence the configuration is axisymmetric; then we show that, if in a isodynamic equilibrium the MS are surfaces of revolution, they are coaxial. We consider then the case of the Stellarator, assuming as coordinate surfaces the MS and on these, as coordinate lines, the lines of force and their orthogonal trajectories which are simply closed poloidal lines. The physical equations allow a simplification of the metric tensor. Finally, we examine the case of the local existence of the isodynamic Stellarator (the non-existence in the compact case is evident). In this case, the metric tensor can be further simplified. The set of the three GAUSS equations and of the three independent CODAZZI-MAINARDI equations for the three families of the coordinate surfaces admits an integral which allows to show easily the non-existence, also locally of the isodynamic Stellarator.

MAGNETIC HELICITY AND THE OHM'S LAW FOR MEAN MAGNETIC FIELDS*

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Magnetic helicity is $\int \mathbf{A} \cdot \mathbf{B} d^3x$ with $\mathbf{A}$ the vector potential and $\mathbf{B} = \nabla \times \mathbf{A}$ the magnetic field. The importance of helicity is that it is approximately conserved by plasma turbulence. The magnetic energy $\int (B^2/2\mu_0) d^3x$, on the other hand, can be rapidly dissipated. Helicity conservation has been used in three types of analysis. First, the magnetic energy can be minimized subject to the conservation of helicity to obtain stable magnetic configurations. Second, the evolution of the helicity in an arbitrary, time dependent, bounded region leads to important equations on the maintenance of plasma currents. Third, helicity conservation constrains the mathematical form of the law for dissipation, the Ohm's law of spatially averaged, or mean, magnetic fields. The mean field Ohm's law permits the study of the effects of resistive instabilities using axisymmetric transport codes. In addition to the three types of helicity analysis, examples of applications will be given. These applications include a stable tokamak with $q < 1$, the possible maintenance of the tokamak current without external power by the interaction of the bootstrap current and tearing modes, and the possibility of MHD current drive in a tokamak.

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

Ion Bernstein modes in the presence of a poloidal magnetic field.*

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The modification of the dispersion properties of ion Bernstein modes in the presence of poloidal magnetic field in a cylindrically symmetric plasma column enclosed by a perfectly conducting cylinder is studied. The general formulation allows for the study of the non-local dispersion relation of these waves. However, due to the smallness of the ion cyclotron radius relative to the slow variation of the plasma parameters in the radial direction we can assume a local approximation radially and study the poloidal propagation by performing a Fourier decomposition of the electrostatic potential. The principal effect introduced by the poloidal field is the change in the effective parallel wave number giving rise to an asymmetry for waves that propagate in opposite axial directions. This creates a modification in the electron Landau damping. Also, the existence of the rotation frequency in the poloidal direction allows for the presence of an extra contribution proportional to the parallel velocity in the resonant denominator which changes the ion cyclotron damping and is present even in the case of vanishing parallel wave number. Specific examples for tokamak parameters will be presented.

Work supported by USDOE.

1986 SHERWOOD THEORY CONFERENCE
April 14-16, 1986; New York, New York

RELATIVISTIC 2-D FOKKER-PLANCK CODE FOR LOWER-HYBRID CURRENT DRIVE*

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The steady-state 2-D relativistic Fokker-Planck equation is solved numerically using the finite-element code TWODEPEP. The equation is written for the distribution function of energetic electrons in momentum space, with a relativistic collision operator in the Landau limit. The performance of the code is verified for the case of an externally applied constant electric field, for which relativistic effects on the runaway tail and the runaway production rate have been previously studied analytically [1]. We then solve the equation with strong rf diffusion to study J/P_d in cases corresponding to experiments where tails extending to 0.5 MeV have been observed.

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* This work was supported in part by Hydro-Québec Project No. 01844-571-59535 and in part by DOE Contract No. DE-AC02-78ET-51013.

A MODEL FOR TFTR OHMIC DISCHARGES*

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A simple 1D transport model that provides a good fit to earlier TFTR Ohmic discharges with significant levels of impurity radiation loss is presented. The radial profiles of the electron temperature, including the broadening due to sawtooth oscillations, are reproduced over a wide range of density and current, by a combination of an anomalous electron diffusion coefficient that is based on a generalization of the Coppi-Mazzucato-Gruber coefficient to cases with significant nonOhmic terms in the electron power balance[1] and a model for the sawtooth crash that used Kadomtsev-type helical flux conservation to calculate the disruption radius from the self-consistent current density profile and the observed sawtooth period. Ion temperatures for these discharges are reproduced by an approximately neoclassical diffusion.

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GYROVISCOUS EFFECTS IN THE STRESS TENSOR FOR TOKAMAK PLASMAS IN THE PLATEAU REGIME

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There has been recent interest in calculating the stress tensor, including the gyroviscous contribution, for toroidally rotating tokamak plasmas in the Pfirsch-Schluter regime. This interest has stemmed from results in unbalanced neutral beam injection experiments that the rate of radial transport of toroidal momentum is very significant. In particular, the full viscosity tensor[1] *has been derived in the Pfirsch-Schluter regime for pure axisymmetric toroidal plasmas.*

However, there exist situations where the toroidal momentum confinement is dependent on a two ionic species plasma, with the main ions in the plateau regime and impurity ions in the Pfirsch-Schluter or plateau regime. Thus, we derive here the gyroviscous contribution to the full stress tensor in the plateau regime for axisymmetric tokamak geometry. The momentum confinement of such a composite plasma can then be computed as a function of impurity concentration.

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Nonlinear Coupling of Tearing Modes in the Reversed Field Pinch*

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The nonlinear evolution of tearing modes is considered a leading candidate to cause the dynamo effect which sustains RFP discharges against resistive decay.[1] RFP profiles typically exhibit instability to tearing modes having poloidal mode number $m = 1$ and toroidal mode numbers $10 \lesssim n \lesssim 20$, and the MHD activity of these modes is commonly observed experimentally.[2] In previous calculations using a full set of resistive MHD equations, the importance of the $m = 2$ modes which couple the adjacent $m = 1$ instabilities was demonstrated[3] by showing and analyzing the stabilizing influence of these couplings upon the $m = 1$ evolution. The present work extends the previous results by considering the evolution of many modes. In particular, it is seen that the nonlinear couplings lead to spectrum evolution similar to that observed experimentally[2] in an RFP discharge having $m = 1$ activity. In addition, by following the spectrum evolution it is seen that nonlinear couplings of the dominant $m = 1$ instabilities by linearly stable coupling modes leads to a broadening of the spectrum toward high n which constitutes a spreading of the magnetic perturbations outward from the core toward the field reversal surface. This spreading, as well as the experimentally similar spectrum evolution, is not observed unless the nonlinear couplings of the $m = 1$ instabilities are included in the calculations.

* 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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Parametric Excitation of an Ion Acoustic Wave by an Electron Cyclotron Wave*

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Recently, the author derived a nonlinear dispersion relation for a circularly polarized electromagnetic wave of a finite wavelength by a kinetic theory which includes an important correction to a dispersion relation previously derived,[1] and applied to a right circularly polarized pump wave of a frequency greater than the right wave cutoff frequency in a low density plasma.[2] More recently, the nonlinear dispersion relation was applied to a left circularly polarized wave in a high density plasma. In a tokamak, an obliquely propagating extraordinary mode launched at the high field side of the resonance becomes a left wave propagating parallel to the confining magnetic field, if the density of the central plasma is higher than the cutoff density. For the electron cyclotron heating experiment on Doublet III, plasma heating, probably at the outer half minor radius, has been observed under such a condition. We investigate one possible heating mechanism, parametric excitation of an ion acoustic wave by a left wave in such a high-density, high-temperature plasma, assuming that all waves are propagating along a constant magnetic field. Our result indicates that the instability is expected to occur with realistic power and results in slow bulk ion heating.

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

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SHERWOOD THEORY MEETING 1986

Analytical Description of Cold Plasma Surface Alfvén Eigenmodes in Slab Geometry*

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Cold plasma Surface Alfvén Eigenmodes (SAE) formed due to the presence of Alfvén resonances near the plasma edge[1,2] are studied. In slab geometry, a single fourth-order differential equation in $E_\perp$ is derived. It is reduced to a modified Bessel equation and an inhomogeneous Airy equation[3] to describe the MHD and SAE fields, respectively. The SAE fields, in contrast to Kinetic Alfvén Waves and Global Alfvén Eigenmodes, are strongly localized near the plasma edge and decay rapidly toward the plasma center. We connect SAE fields asymptotically to the MHD fields in the plasma interior, and to the vacuum solutions at the edge. Consequently a dispersion relation to find the complex eigenfrequencies is obtained. The results agree accurately with the impedance resonance frequencies and their widths in the antenna-driven numerical solutions. The importance of these modes is enhanced by the fact that in the presence of impurities they can dissipate most of their energy in the two-ion hybrid layer near the center. This problem will also be discussed.

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

NONLOCAL LOWER-HYBRID-DRIFT WAVES AND ONE-DIMENSIONAL TRANSPORT MODELING IN A FIELD REVERSED CONFIGURATION*

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We have reexamined the one-dimensional transport theory for field reversed configurations taking into account global lower-hybrid-drift turbulence. Extending previous work[1] for nonlocal electrostatic lower-hybrid-drift theory, we have determined the spatial character of lower-hybrid-drift eigenmodes in the separatrix region of a field reversed configuration. Surprisingly, we have found that the transport model based on the more comprehensive "global" theory of the lower-hybrid-drift theory results in transport coefficients which are very similar to those based on the simple "local" lower-hybrid-drift theory. The reason for this is as follows. The nonlocal theory of the lower-hybrid-drift predicts a sequence of eigenmodes with differing eigenvalues and spatial extent. It is found that if a particular eigenmode is considered and the radial points which mark its radial extent are noted, then the eigenfrequency and growth rate associated with that eigenmode will have approximately the same value as the frequency and the growth rate naively calculated on the basis of the local conditions at the radial edges of the eigenmode.

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

Numerical Simulation of Transport in Field Reversed Configuration *

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The compact torus transport code CTT has been applied to the simulation of the transport time scale evolution of a FRC plasma. The calculation proceeds by alternating between the calculation of a 2-D axisymmetric equilibrium and 1-D transport. The equilibrium calculation uses flux surface coordinates and finite elements. The transport calculation consists 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: Braginskii 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. In the FRC plasma there are points where the magnetic field is zero (o-point and x-point). In order to properly describe the transport near these points, one must use transport coefficients which are correct for any magnetic field value. Results of the simulation are compared to the FRX-C experiment at Los Alamos National Laboratory. for the high density experiments (20 mTorr) experiment and simulation are in good agreement when the electron-ion collision frequency is multiplied by a factor of 10.

*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.

SHERWOOD THEORY MEETING 1986

Momentum and Energy Confinement in Tokamaks with Neutral Injection*

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The observed relation between momentum and energy confinement times ($\tau_\phi \approx \tau_E$) in neutral-injection-heated tokamaks has remained a puzzle for a long time. Recently, experimental results have indicated that ion thermal conduction may be comparable to electron transport in NBI-heated tokamaks. Such anomalous ion thermal loss is usually attributed to ion-temperature-gradient (η_i) driven turbulence. The η_i mode offers the possibility of a simple explanation for the $\tau_\phi \gtrapprox \tau_E$ puzzle. The η_i mode is essentially a sound wave which naturally couples to a sheared parallel ion flow $v_{\|0}(r)$. Thus, η_i-mode turbulence can produce a shear viscosity which transports ion momentum (via $v_{\|0}(r)$) out of the plasma.

In this work, the effect of a sheared, parallel flow $v_{\|0}(r)$ on η_i-mode turbulence has been investigated. For the case where $v_{\|0} < c_s$, a (quasilinear) transport calculation which extends previous work[1] predicts that $\chi_\phi \approx \chi_i$. Furthermore, it has been determined that the shear-flow $v_{\|0}(r)$ results in additional enhancement of the η_i-mode growth rate and mode width. A more detailed nonlinear theory and a kinetic treatment of the $v_{\|0} \sim c_s$ regime are in progress.

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1. G. S. Lee and P. H. Diamond, IFSR #209.

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

Another FRC Equilibrium Code, R. B. Webster Purdue Univ. ,[1] and J. L. Schwarzmeier Los Alamos National Laboratory.[2] A new numerical method for the calculation of two dimensional elongated FRC equilibria is presented. This method is highly vectorizable and runs in reasonable times on the CRAY-2 (eg., for the Heaviside p' equilibrium with an elongation of 5, less than 1.5 CPU minutes were used). For elongated equilibria, excellent radial pressure balance is obtainable (eg. for the above Heaviside profile, the pointwise deviation in $p + \frac{1}{2}B^2$ is less than 1%, and the difference in the field null pressure p_0 and the vacuum field pressure $\frac{1}{2}B_0^2$ satisfies $|p_0 - \frac{1}{2}B_0^2| < 5 \times 10^{-4} p_0$).

In the present method, the poloidal flux function ψ is computed by solving the Grad-Shafranov (G-S) equation in the (μ, z) plane, where μ is a coordinate that results from the application of a stretching transformation f^{-1} to r^2. In these coordinates, the G-S equation becomes:

$$\Delta^* \psi \equiv 4f(\mu)\left(\frac{1}{J^2}\frac{\partial^2 \psi}{\partial \mu^2} - \frac{1}{J^3}\frac{\partial J}{\partial \mu}\frac{\partial \psi}{\partial \mu}\right) + \frac{\partial^2 \psi}{\partial z^2} = -f(\mu)p'(\psi) \qquad (1)$$

with, $r^2 = f(\mu)$, $J(\mu) = \frac{\partial f}{\partial \mu}$. A similar stretching transformation was recently added to the Hewett-Spencer code; [3] where it proved to be useful in resolving steep gradients near the separatrix while maintaining a relatively small number of radial knots. The present method differs from previous methods in the way in which ψ is represented, and the way in which the resulting discretized equations are solved. As a representation of ψ we take: $\psi_j(\mu) = \sum_i a_{ij} S_i(\mu)$, where, j denotes the axial position and the functions $S_i(\mu)$ are cubic splines evenly spaced in μ. With this representation, axial derivatives are evaluated using finite differences, while radial derivatives are determined by differentiating the splines. The solution of the nonlinear problem is then accomplished by iterating on the linear system $A\psi^{k+1} = b^k$, where A and b^k are the matrix and vector representations of Δ^* and $-r^2 p'(\psi^k)$ respectively, and the superscript denotes the iteration number. These representations are formed using the Galerkin approximations. The resulting linear system is solved directly using elimination. Convergence is achieved when $\max_{ij} |b_{ij}^{k+1} - b_{ij}^k| < \epsilon$. Accuracy of the representation is judged by substituting the converged representation for ψ into the G-S equation (1) and examining the error pointwise.

The present method possesses several advantages over previous methods. The Hewett-Spencer code can have erratic convergence properties, with convergence depending strongly upon the separatrix radius and length of the FRC. In some instances, increasing the number of radial knots in order to resolve the steep gradients required for elliptic equilibria can lead to a loss of convergence. In the present method, convergence is monotonic in iteration number and does not appear to be sensitive to the length of the FRC or the number of radial splines. This allows for the computation of equilibria for which the toroidal current j_θ has steep gradients; although, in general it is $||\Delta^*\psi + r^2 p'(\psi)||_2$ rather than $||\Delta^*\psi + r^2 p'(\psi)||_\infty$ (pointwise error) that is small. Shumaker[4] has found elongated FRC equilibria that match experimental data well using Grad's entropy formulation in flux coordinates. Unfortunately, his scheme has singular behavior of $p'(\psi)$ at the separatrix and it is not clear what impact this behavior has on the solution. In the present method, there is no singularity in any quantity at the separatrix, and since the solution is not performed in flux coordinates, non-MHD equilibria having purely poloidal magnetic fields can be determined, as Ampere's law for such equilibria is simply $\Delta^*\psi = -rj_\theta(r, \psi)$.

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STABILITY OF m=0 ISLANDS IN THE RFP*

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Previous work has indicated the importance of m=0 perturbations for the RFP dynamo both theoretically[1] and experimentally.[2] The persistence of these perturbations in ZT-40M is apparently stronger than would be indicated by simulation results. One possible explanation for this effect is the stability of these islands themselves. This possibility will be discussed and numerical results presented.

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*Work performed under the auspices of the USDOE.

EFFECT OF FLOW SHEAR ON NONLINEAR TEARING MODES

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The effects of a large flow shear on the nonlinear growth of a tearing mode are investigated. Large flows in the vicinity of reconnecting x-points are commonly encountered in space plasma situations; in tokamaks, the radial variation of neutral beam induced rotation may constitute a significant flow shear near magnetic islands. The shear in the flow, in conjunction with the frozen-in tendency, may be expected to influence the dynamics of nonlinear island growth. A set of coupled equations for arbitrary sized islands is derived describing the time evolution of the magnetic flux, ψ, and the electrostatic potential, ϕ. Flows up to a fraction of the Alfvén speed are allowed. The equations are specialized to the case of thin islands where the constant-ψ approximation is valid. The effects of this flow on the Rutherford growth rate as a function of the strength of the shear will be discussed.

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

Parametric Interaction of ICRF With Low Frequency Turbulence in Tokamaks*

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Recently, Morales *et al.*[1] studied the interaction of magnetosonic ICRF with density fluctuation and showed that ICRF can be effectively scattered by the turbulence and converted into Bernstein waves. They, however, have not considered the problem of the effect of ICRF on the turbulence which has relevance to anomalous transport in an rf heated plasma. In this work, the self-consistent theory of parametric interaction of ICRF with low frequency turbulence is studied. We consider the decay of fast wave to an ion Bernstein wave and a trapped particle mode. Both collisional and collisionless modes are considered in a Krook model. The coefficients of nonlinear interaction are calculated. Their significance to anomalous transport in an ICRF heated tokamak plasma will be discussed.

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EFFECT OF TOROIDAL FLOW ON BALLOONING MODES*

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It has been suggested [1] that ballooning modes in a tokamak may be stabilized by inducing rapid toroidal rotation with flow velocities of the order of the sound speed. The effect of such flows on an equilibrium is to produce an additional shift of the magnetic axis which has been shown by a model calculation [2] to be comparable with the usual Shafranov shift without flow. Numerical results from equilibrium codes with flow [3] has confirmed the existence of this additional shift for a large class of profiles. This raises the interesting possibility that toroidal flow, by causing an additional shift, may dig a deeper diamagnetic well and thus aid the stable access to or reduce the second region stability boundary. The ballooning mode formalism for three-dimensional equilibria with flow, generalises naturally [4,5]. For model axisymmetric equilibria, we integrate numerically the equations along the field-line to obtain eigenvalues. Using the variational principle of Frieman and Rotenberg [6], we reexamine the sufficient conditions for stability.

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Quasilinear and Steady Electric Field Effects on Electron Cyclotron Heating*

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A new three dimensional bounce-averaged Fokker-Planck/quasilinear code CQL3D[1] is used to assess effects on ECH power absorption of QL diffusion and of an applied steady Ohmic electric field. Plasma conditions are assumed to be those pertaining to the Doublet III fundamental ECH heating experiment[2] using inside-launch of extraordinary mode energy. The CQL3D code consists of 2D-in-velocity-space bounce-averaged Fokker-Planck codes which are run in tandem on each of several radial flux surfaces, thereby simulating three dimensional effects. Coupling between flux surfaces results from solution of the 2D-in-configuration-space wave energy ($\mathcal{E}$) transport equation

$$\nabla.(\mathcal{E}\,\vec{v}_g) = p_{\mathrm{abs}} \ ,$$

which is integrated using power absorption p_{abs} calculated consistently from the quasi-linearly distorted electron distribution functions. Soft x-ray spectra are calculated and compared with Doublet III observations of a radially hollow SXR profile which occurs in low density $[n_e(0) \leq 2 \cdot 10^{13}\ \mathrm{cm}^{-3}]$ experiments with the ECH resonance layer passing through the plasma magnetic axis.

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*This is a report of work sponsored by the Department of Energy under Contracts No. DE-AC03-84ER53158 and No. W-7405-ENG-48.

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A Fully Implicit Field Solver for 3D Particle Simulation Codes*

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It is often desired to solve Maxwell's equations by implicit methods when the time scales of physical interest greatly exceed the signal transit periods that would otherwise dictate a very small timestep should an explicit method be used. In our studies of the tilting mode in a reversed field theta pinch we have recently built a plasma simulation code that uses the Darwin approximation to Maxwells's equations. We have developed a matrix solver that solves a very general class of coupled partial differential equations. Many different finite difference or finite element operators are allowed and the number of coupled equations is arbitrary. We have generalized an earlier preconditioned conjugate gradient method ILUCG, that solved scalar PDE's in three dimensions. Use of indirect indexing allows one to write a compact and readable source code that would otherwise be intractable. The new feature of vector indirection on some of the Cray multiprocessor computers allows us to obtain vector speed from this new form. In our application each scalar field has a 27 point operator stencil. When the three scalar fields are coupled the generalized operator has 135 stencil points. The associated global operator matrix has 99 non-zero diagonals. We shall present results from the Maxwell solver to illustrate the favorable speed and convergence properties. Also we will show how the convergence properties are improved as the number of coupled equations increases. Finally, we mention the general applicability of the method to larger systems such as the fully implicit MHD equations.

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

Normal Mode Simulation as a Test for 3-D Particle-in-Cell Code *

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Progress on QN3D is presented. QN3D is a 3-dimensional hybrid particle-in-cell code that treats ions as particles and electrons as an inertialess fluid. The electromagnetic fields are solved in the Darwin limit. As a test of QN3D, the normal modes for a cold magnetized plasma in a periodic domain are calculated. The resulting dispersion relation and consistent field perturbations are presented. The code is initialized to model these modes by specifying initial field perturbations and the wave number. The code is monitored to observe the oscillation of the fields, and the results are Fourier analyzed in time to determine the frequency of this oscillation. The results are compared to the analytic calculations.

*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.

Turbulence Models in Plasma Physics*

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We investigate the usefulness of turbulence models in plasma physics. We use numerical simulations based on ensemble averages to ascertain the validity of the approximations fundamental to the model equations. Thus we study higher-order moments, the appearance of substructures, and the applicability of the fluctuation-dissipation theorem. We start with the simple two-dimensional one-field drift-wave equation[1], and progress to more complicated multifield systems. We find it is necessary to generalize standard closure schemes to the two-field[2] or three-field equations[3] in order to adequately apply closure schemes such as the test-field model of Kraichnan.[4]

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

SHERWOOD THEORY MEETING 1986

Collisional Drift-Wave Turbulence with η_e Effect*

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A renormalized theory of collisional drift-wave turbulence is developed from the hydrodynamic two component fluid equations. Including the effect of finite η_e from the T_e equation, collisional drift-wave turbulence is described by reduced two-field equations which generalize previous turbulence studies. From the two-field equations, we obtain the renormalized set of equations while treating the electron and the ion nonlinearities on the same footing. In the regime of $\omega \sim d_k \sim b_k \ll k_{\|}^2 v_{te}^2/\nu_e$, we show that the renormalized set of equations reduce to the simpler form of one-field equation of the previous theory (Terry-Horton equation[1]). The saturated fluctuation levels are proportional to ρ_s/r_n and the wavenumber spectrum decreases as k^{-3} at low k and k^{-5} at high k. The anomalous particle flux Γ and electron thermal flux q_e are calculated from the particle and thermal balance equations.

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

ICRF Fundamental Minority Heating in Inhomogeneous Plasmas,* H. ROMERO and J. SCHARER, Electrical and Computer Engineering Department, University of Wisconsin, Madison, Wisconsin 53706 -- We present in this paper a theoretical analysis of ICRF fundamental minority heating leading to a set of coupled linear differential equations for the electromagnetic field. The wave differential operator is obtained through a direct solution of Vlasov's equation assuming the smallness of the parameters $\rho d(\ln|\vec{E}|)/dx$ and ρ/L. First order terms in the quantity ρ/L must be included self-consistently in the analysis of this plasma heating scenario to insure certain limiting properties of the resulting wave differential operator. In particular, the operator obtained in this work can be shown to be self-adjoint in the limit $k_{\parallel} \to 0$ indicating that the power absorbed by the plasma is zero in this limit. Other effects explicitly included in our formalism are strong wave damping of the ICRF wave field (on a scale length comparable to the local wavelength) and linear mode conversion between the fast and ion Bernstein modes in the vicinity of the resonance layer. Comparison of the results with those obtained using a gyrokinetic formalism will be made. Field solutions and power deposition profiles are obtained numerically throughout the strong absorption region for reactor-sized tokamaks such as JET. The evanescent ion-Bernstein mode contribution is obtained on the low-magnetic side of the tokamak employing a singular perturbation scheme. Initial results indicate higher direct absorption by the majority species than previously predicted.

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*Research supported by DOE Contract DE-AC02-80ER53104 - Task III.

SHERWOOD THEORY MEETING 1986

Fusion Sustained Current in the Field-Reversed Configuration*

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It is shown that energetic charged particles generated by thermonuclear fusion reactions in the field-reversed configuration give rise to a directed flow parallel to the plasma current. This is because of the selective magnetic confinement of the energetic particles which requires $p_\theta - r_s v_0 > 0$, where p_θ is the canonical angular momentum, r_s the separatrix radius, and v_0 the birth speed of the fusion product. The physical mechanism for containment is closely related to the betatron orbit theory. The equivalent current density of directed charged fusion products can be comparable to the background plasma current density. The initial energy of fusion α-particles for DT fusion is 3.6 MeV, while that of fusion proton in D^3He is 14.7 MeV. Thus, an FRC with a few tesla magnetic field yields a multi-MA current. A similar effect exists for other confinement configurations such as a tokamak, but is much weaker than for the FRC.

Our study shows that a fraction of the charged fusion particles are in the containment region. This selective containment gives rise to a current that supports the reversed field configuration. The subsequent collisions are primarily drag-like, from which we can prove that the particles remain confined until they reach low energies. The current profile in a strong field case exhibits a hollow structure with a positive current on the rim and negative or zero inside the rim of the (rz) cross-section $(r > 0)$ of the FRC configuration. In this case the fusion sustained current would make the overall magnetic field weak inside of an FRC, thus increasing the $\langle\beta\rangle$ value closer to unity. The present idea may be understood as the Fusion Sustained Astron Configuration, in which the fusion beam could stabilize MHD modes that are otherwise unstable. We shall discuss our analysis and simulation studies. Impact of this effect on an advanced fuel fusion reactor will be stressed.

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

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ON THE PRESENCE OF THE LOWER HYBRID DRIFT INSTABILITY IN THE FIELD REVERSED CONFIGURATION*

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The Lower Hybrid Drift instability has been predicted to be one of the most important instabilities contributing to the anomalous transport in the sheath region of the Field Reversed Configuration experiment (FRC). Waves having the properties expected of Lower Hybrid Drift fluctuations were found in the sheath region of the INTEREX experiment.[1] Although this experiment was a theta pinch rather than an FRC, it has been presumed that the physical conditions in the sheath region, where the density falls rapidly, are similar to those in the sheath region of the FRC, so that the fluctuations observed in the sheath regions of the two experiments should be similar. However, when the sheath region of an FRC was studied[2] experimentally with similar techniques, no Lower Hybrid Drift fluctuations were found. It has been suggested that the difference between the two experiments may be due to temperature gradient effects or collisional effects.

This research is intended to quantify how the different profiles and parameters of the two experiments can influence the behavior of the Lower Hybrid Drift instability and other possible instabilities. Previous work, utilizing nonlocal theory, has shown[3] that a density profile in the presence of constant temperature profiles is Lower Hybrid Drift unstable. This work is extended to the case of temperature profiles dropping off as the density drops off. In the case of constant temperature and density gradients in the same direction, local theory has indicated that a large enough temperature gradient will stabilize the mode.[4] This result will be generalized to the case of real profiles having variable density and temperature profiles (not necessarily having the same gradients at the same point in space) to ascertain whether or not the Lower Hybrid Drift Instability can be stabilized under these conditions. The effects of collisions will also be considered.

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*Work performed under the auspices of the USDOE.,

Role of Surface Effects in RF Stabilization of Axially Symmetric Systems.

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Knowledge of ICRF electric field profiles is important for applications to the heating and RF stabilization of MHD instabilities. With these applications in mind, electric field profiles of plasma column eigenmodes have been recently analysed[1]. The model used assumed $E_{\parallel}$ small compared to $E_{\perp}$. Such an approach describes well the interior of the plasma and thus is well suited for the RF heating applications. However the stability properties may depend strongly on fields on the plasma surface. There electric fields are enhanced due to the lower density. Additionally, near the plasma edge a surface wave can exist[2] which has a significant $E_{\parallel}$. This wave is the cylindrical analog of the ordinary mode below cut-off and is radially evanescent. In the present work we compute the contribution of these surface modes to the ponderomotive force and analyse their role for stability.

Supported by U.S. DOE contract DE-AC02-78ET51015

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Trapping/detrapping orbits in nonsymmetric toroidal magnetic fields*

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In a nonsymmetric toroidal magnetic field, particles can become trapped in local magnetic wells produced by, e.g., the discrete toroidal field coils in a tokamak or the helical coils of a stellarator. The locally trapped particles execute large drift orbits that can intersect the wall. These particles can supply the dominant transport channel. The transport rate depends strongly on the trapping probability, the probability per half-bounce-period that a toroidally trapped particle becomes locally trapped.

Previous calculations yield a trapping probability that exceeds unity and, in fact, diverges for particles that trap near $\theta = 0$ or π. In the present work, this singularity is resolved. A general formalism for calculating the trapping probability is obtained. It is shown that the probability can be simply expressed in terms of the Poisson bracket of the separatrix energy and the separatrix action. The calculation includes the effect of the ambipolar field.

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

ION TEMPERATURE GRADIENT DRIVEN DRIFT MODE IN A REVERSED FIELD PINCH

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Attention has recently been focused on the ion temperature gradient driven drift instability as a possible contributor to anomalous transport in the Reversed Field Pinch (RFP). In particular, An et al. [1] have considered some transport consequences of the coupling of the ion temperature gradient driven drift mode with the magnetic curvature driven resistive interchange mode (resistive g-mode). The potential for such a coupling is enhanced (and complicated) by the somewhat unusual effects of magnetic shear on the ion drift mode, e.g., the most unstable radial eigenmode is typically not the one with the least number of modes and the tendency of increasing shear is to actually increase the growth rate of the lowest eigenmode while decreasing the growth rates of the higher eigenmodes [2].

With this motivation, we reconsider the linear stability analysis of the ion temperature gradient driven drift mode with an emphasis on understanding how some particular parametric conditions characteristic of an RFP can affect this mode. We place initial emphasis on examining the heretofore unstudied effect of strong applied current on the ion drift mode. Indeed, under typical RFP conditions, the free energy associated with the applied current exceeds the free energy in the diamagnetic currents which give rise to the ion drift mode. Furthermore, the applied current manifests itself as a desymmetrizing influence in the radial eigenmode equation for the ion drift mode. This suggests the possibility of different effects on eigenmodes with different parity and may also affect the ability of ion drift modes to couple with resistive g-modes.

We base our analysis on a slab model kinetic theory in order to directly address the recognized importance of adiabatic electrons on this mode [1]. Because the magnetic shear necessitates a nonlocal treatment and because primary interest is on understanding a competition of effects on higher eigenmodes, our results are largely numerical.

In this study, substantial use was made of the ANLYZ expert system for facilitating parametric analyses.

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Stabilization of the m=1 Interchange Mode by Applied ICRF*

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In previous work the perturbed nonlinear force density on an MHD fluid element due to both the ICRF direct ponderomotive and sideband mode coupling terms was presented. This enabled a calculation of the marginal stability criterion for the m=1 rigid shift interchange mode in axisymmetric tandem mirror geometry. This analytical work is extended to show explicitly that ICRF stabilization of the m=1 mode vanishes as the antenna and conducting walls are removed from the proximity of the plasma. That is, the plasma cannot "lean" on the high-frequency fields themselves but only on the rigid structures which support them. To ascertain the degree of proximity required for a practical stabilization scheme, and to compare the theory with stabilization experiments, the results of a detailed numerical study will also be presented. For far field fast wave stabilization (eigenmode "leaning" on a conducting wall) it is shown that an optimal wall position exists. Even at the optimal position ponderomotive and sideband terms tend to cancel to a large degree. For near field stabilization (fields "leaning" on an antenna) the results depend sensitively on the $k_{||}$ spectrum of the antenna, relative to the values of $k_{||}$ which imply propagating ICRF waves and sidebands. Application to Phaedrus will be discussed.

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

Pressure Surface Distortion by ICRF and Magnetic Error Fields*

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In mirror geometry the constant-pressure surfaces are determined by the parallel current constraint. This constraint is trivially satisfied for axisymmetric or quadrupole-symmetric mirror fields. However, other multipole magnetic field components or ICRF ponderomotive effects enter the parallel current equation in a non-trivial way. The extra terms cause a shift of the plasma column and/or distortion of the pressure surface shape. The geodesic and normal projections of the curvature on the distorted surface lead to a modification of the curvature drive for stability and radial transport. This effect is examined for two cases relevant to present experiments: magnetic error fields (~cos θ) due to misaligned coils, and asymmetric ponderomotive effects associated with ICRF heating. The former application may be relevant to the observed neoclassical transport near the magnetic axis in TMX-U, whereas the latter may explain the shift in the plasma column in TARA during ICRF heating with the slot antenna.

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*Work supported by U.S. Department of Energy Contract DE-AC03-76-ET52037.

COMPARISON OF PLASMA FORMATION METHODS IN THE COAXIAL SLOW SOURCE*

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A 2-D MHD code[1] is used to model 3 operating scenarios of the Coaxial Slow Source (CSS): independent pulsing of inner and outer coils,[2] parallel operation[3] to impose equal flux values on both coils, and passive outer coil. Optimization of the trapped flux, plasma energy and the confinement time scales of each method is explored. The parametric dependences on external circuit and plasma transport models are analyzed to find desirable operating conditions for the future experiment. The numerical code utilizes a semi-implicit scheme[4] for the momentum equation and implicit differencing of the diffusion equations to allow an arbitrary time step. Thus, both fast wave steepening and slow diffusive phenomena are efficiently computed.

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 DOE/ER/53223-7

ALTERNATING DIMENSION FORMULATION OF NEOCLASSICAL PLASMA TRANSPORT IN AXISYMMETRIC TOROIDAL SYSTEMS*

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ABSTRACT

Based on the conservation laws, the moment equations of Boltzmann equations and ions, and the drift kinetic approximation in strong magnetic fields, a consistent system is developed for the plasma transport in the neoclassical regime. It is found that Grad's Alternating Dimension formulation (1 1/2 D algorithm) for the classical plasma transport can be readily extended to the neoclassical regime. The leading order pressure balance, governed by the Grad-Shafranov equation for the axisymmetric configuration, is used to determine the geometry of magnetic flux surfaces, and the remaining transport system is then averaged over the flux surfaces to obtain a one-dimensional system. The general theory will be applied to the study of a special case in the tokamak parameter range.

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*This work was supported by U.S. Department of Energy Grant No. DE-FG02-86ER53223.

SHERWOOD THEORY MEETING 1986

Transport During Transient Plasma Perturbations in TEXT *

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Transport during fast current ramping[1,2] on TEXT is re-examined and initial studies of electron cyclotron heating are pursued. Previously, it has been shown that current penetration and heating during ramping at $dI/dt = 8$ MA/sec in ohmic discharges can be simulated[1] without invoking anomalous resistivity, or thermal diffusivity beyond what is required to describe the steady state. The latter includes large edge losses which are unexplained by any theory of which we are aware (larger even than the Coppi-Mazzucato value for $r > r_{q=2}$). However, because of this large edge transport the simulations were unable to reproduce the experimentally observed edge heating and flattening of the T_e profile during the first 20 msec of the ramp. This result is somewhat contrary to our intuitive expectations. It is shown here that the observed T_e profiles can be simulated by transiently *enhancing* χ_e near the $q = 2$ radius, and simultaneously *reducing* χ_e at larger radii. Speculations on the physical causes of this effect and their possible relation to profile consistency arguments[3] are given.

To prepare for electron cyclotron heating experiments proposed for TEXT, auxiliary heating simulations have begun using transport models which have described the ohmic steady state.[4] It is argued that, as in the current ramping studies, carefully comparing the transient phase of the heating process with experiment will help to elucidate the physical processes of profile modification (or profile consistency).

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* Work supported by the U. S. Department of Energy Contract #DE-AS05-76ER 53193

High- q Simulations of Tearing Modes*

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Recent work[1,2] using trapped electron and ion temperature gradient drift wave models has shown remarkable success in describing many features of tokamak confinement time scaling. However, the models have little or no current (or q) dependence. To obtain the observed shrinkage of temperature profiles at high-q and the favorable current scaling of beam heating confinement time, it is necessary to assume the existence of a mechanism to progressively degrade the edge confinement with increasing q. Here we investigate whether or not low-m tearing modes can provide this mechanism. It is well known that tearing modes are generally less unstable at high-q. Nevertheless we use a resistive MHD code to test whether low helicity islands can provide sufficient nonlinear pumping of high helicity islands.

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

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PLASMA POTENTIALS IN THE DIVERTOR REGION OF STELLARATORS*

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A model for the electrostatic potential variation along magnetic field lines is developed and applied to the divertor region of stellarators, especially ATF and Heliotron. The model assumes collisional flow up to the last magnetic mirror point before a field line strikes a surface. The electrons are assumed to obey a Boltzmann distribution, and a generalized Bohm sheath condition is imposed. The ion dynamics between the last mirror point and the wall is assumed to be collisionless. Quasineutrality then determines the electrostatic potential profile along the field line. Variations of the order of T_e are obtained between the last mirror point and the plasma side of the sheath. The potential drop across the sheath itself is reduced somewhat by the upstream variation in the magnetic field.

*Work supported by Martin-Marietta Energy Systems Contract 19X-27434C, Mod. 1.

THE EFFECT OF TOROIDAL FIELD ON THE STABILITY OF HELIOTRON E*

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Calculations[1] of low n mode stability for Heliotron E give beta limits between 1.4 to 2%. These theoretical predictions are compatible with the present experimental results.[2] However, in Heliotron E operation, no use has yet been made of the toroidal field coils, which can greatly change the range of the rotational transform. It is of great interest to find out if its present beta capability can be improved by the use of those coils.

The effect of the toroidal field is quite important. The addition of a modest toroidal field moves the $\iota = 1$ surface to a region of high shear, stabilizing the (m=1;n=1) mode, which is the most unstable mode for Heliotron E. Due to this effect, the critical beta increases with the toroidal field. The n=1 mode is totally stabilized when the toroidal field is 5 to 15% of the total field, and the plasma can gain stable access to the second stability regime. This stabilization effect is operative for zero-current equilibria but is not effective for flux-conserving equilibria. Therefore, in Heliotron E, slow heating should be more efficient than fast heating.

It is interesting to note that the mechanism for the plasma self-stabilization is, in this case, very different from the case of ATF.[3] For Heliotron E plasmas, the stabilization is mainly due to the increase of shear at the $\iota=1$ surface, instead of the deepening of the magnetic well.

Since the shear is the dominant stabilizing effect, a weak stabilization can be expected only for the resistive instabilities. This is certainly the case for the linear stability. However, nonlinearly the stabilizing effect is more pronounced, and the saturated level of fluctuations decreases with the added toroidal field.

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

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CONSISTENCY OF NONLINEAR SELFDAMPING

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We have calculated the correlation function for selected modes of decaying Navier-Stokes turbulence produced by our two-dimensional spectral convection code ASTER [1]. The ensemble-averaged Fourier transform $I(k,\omega)$ thereof should be peaked with a half-width $\Gamma(k)$ for consistency with the DIA theory of nonlinear self-damping [2]. Our results are consistent with this theory.

* Work supported by the National Science Foundation and the Department of Energy.

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STABILITY OF AN AXISYMMETRIC MIRROR WITH AN ENERGETIC ION COMPONENT

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Numerical results of a study of the stability of an axisymmetric mirror with a large orbit energetic ion component to finite azimuthal mode number interchange and ballooning modes will be presented. The analysis makes use of a dispersion functional[1,2] in which the eigenfunction is represented in terms of a complete set of global basis functions, providing a necessary and sufficient condition for stability. The phase-space autocorrelation functions of energetic particle orbits, which appear in the dispersion functional, display periodic as well as stochastic features that will be discussed in some detail. Results are presented for energetic ions represented by a rigid rotor distribution function and for a simple Maxwellian. Both cases exhibit competing stabilizing and destabilizing effects.

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Poloidal Electric Field Generated by Electron Cyclotron Heating in a Collisional Tokamak Plasma*

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It was previously suggested[1] that electron cyclotron heating can alter the particle orbits in a tokamak in such a way as to create poloidal density variation on a flux surface resulting in a poloidal electric field. An estimate of its amplitude was obtained for the "banana" regime with the bounce frequency much larger than the collision frequency. Here, we extend the calculation to the collisional regime with the collision frequency much larger than the transit frequency. This is relevant at the edge region for electron cyclotron heating of high density plasmas. The two new findings are: poloidal density variation can result from the Doppler resonance nature of cyclotron heating; and the poloidal potential normalized by temperature can be of the order of the inverse aspect ration. The effect of this potential on transport will be discussed.

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

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DOE/ER/53223-5

NONLOCAL ANALYSIS OF THE BUDDEN-TUNNELING PROBLEM

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ABSTRACT

We study the interaction of electrons with electromagnetic waves when the equilibrium magnetic field is approximately parallel stratified near the cyclotron resonance surface, and when for small electron density, the Budden tunneling effect is present. Near the resonance surface the cold plasma theory is invalid and the Vlasov-Maxwell equations are solved in a boundary layer. The asymptotic solutions can be found analytically (except for the reflection coefficient for the low-field incidence case). However, in order to find the energy deposition profiles, we have to solve numerically integro-differential equations. Analytical results for the asymptotic solutions and numerical solutions across the boundary layer will be presented.

*This work was partially supported by U.S. Department of Energy Grant No. DE-FG02-86ER53223.

A PARTIALLY ELLIPTIC 3-D MODEL OF RFP DYNAMICS*

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Previous three-dimensional, nonlinear single-fluid, resistive MHD simulations of reversed-field pinch (RFP) dynamics have yielded a conclusive numerical demonstration of the RFP dynamo effect. Based on certain features of these results and problems encountered in these simulations a new model has been constructed, the solution to which must at this stage still be obtained numerically, that may lead to a better understanding of the RFP dynamo effect from a dynamical basis; and, in addition provide a starting point for analyzing the effect on plasma energy transport of long-wavelength MHD instabilities.

Previous simulations have shown that a single-helicity MHD model will settle into a steady-state consistent with the resistivity profile (so called helical ohmic state) with inertia unimportant (but with flow velocity) if the proper boundary conditions are specified. These states may have a symmetric (in a cylinder) component of axial magnetic field that is reversed, but helical components of the field at the edge are large. If the third dimension is then allowed these states will in general be unstable to each other. The intersection of all such 2-D states is in a cylinder the inertialless "transport" description for which a possibly time-dependent solution can be effected numerically utilizing a flux coordinate description (in a torus the Grad-Shafranov equation results).

Our model makes only one principal assumption: the neglect of inertia on the symmetric component of the momentum equation (hence partially elliptic) in cylindrical geometry. All equations are then transformed in terms of flux coordinates and new "adiabatic" dependent variables are derived. This results in, among other things, an evolutionary equation for q(r) formally containing an "α effect" without any spatial scale assumptions. Numerical results of this model in the quasi-linear limit will be presented if available.

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*Work supported by the USDOE.

MAGNETIC DIVERTOR STABILIZED CONFINEMENT DEVICES*

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A Magnetic Divertor is shown to stabilize m=1 fluctuations in a mirror cell.[1] For a sufficiently long cell higher azimuthal modes can be stabilized by FLR effects. The stabilization is a result of a ring null that would be created in this configuration. Electrons that enter the null can stream azimuthally and thereby "short-circuit" m=1 fluctuations. To assure that the plasma core is stabilized by the ring null located near the plasma edge, some pressure must be maintained on the flux tube containing the null.

This stabilization scheme, can be tested in an axisymmetric tandem mirror central cell. It can also serve to stabilize a confinement device in which the ends of two long axisymmetric mirror cells are connected by elements that exhibit autonomous equilibrium (such as a DRAKON[2]). Such a device preserves the advantages of a tandem mirror, i.e. high beta, steady state, cylindrical geometry but eliminates the need for axial plugging and quadrupole elements. It can be expected to exhibit toroidal confinement, and the potential for ignited operation.

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Modeling and Transport Simulations of F - Θ Pumping in the RFP*

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The necessity of m=1 modes for current drive has been shown in 1-D geometry by using Faraday's and Ohm's laws and regularity conditions on the magnetic axis. An m=1 tearing mode that generates poloidal flux (necessary for current drive) has been identified in the form of an unstable off-axis parallel current peak. A 1-D analytical model based on the Kadomtsev reconnection model has been developed to describe the effects of this instability. A scoping of the F - Θ space has been performed using a polynomial expansion for the parallel current profile, a linear resistive stability code and the 1-D reconnection model to find where this mode is unstable, the relative increase of poloidal flux and the size of the reconnecting region.

A comparison between 1-D plasma transport simulations and the results from the F - Θ pumping experiment, currently under way on ZT-40M at Los Alamos, will be presented.

* Work performed under the auspices of US DOE.

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Lower-Hybrid Sloshing-Ion Instability in TMX-U*

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Recent experimental results suggest enhanced particle losses near the inboard sloshing-ion turning points of the TMX-U end cells.[1] Calculations indicate that the turning-point region should be unstable to ion-ion modes near the lower-hybrid frequency.[2] Electron interactions make the modes convective and wavelength constraints can push the instability up in frequency, eventually becoming CLC[3,2]. The unstable frequencies lie in the range $\omega_{LH} < \omega < (T_{SI}/T_e)^{1/2}\omega_{LH}$. We find appreciable growth (despite convective stabilization) for TMX-U parameters. The modes may be associated with the sharp density limits observed experimentally in TMX-U; appreciable growth is found when the length of the driver region exceeds about $10^6(T_{SI}/n_e)^{1/2}$.

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* Work performed for U.S.D.O.E. by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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SHERWOOD THEORY MEETING 1986

Nonlinear Fluid Equations for Toroidal Resistive Modes in the Plateau Collisionality Regime*

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Recent attempts[1] to extend MHD fluid equations for toroidal plasmas to long mean free path regimes have uncovered the importance of neoclassical dissipative processes – particularly rotation damping and bootstrap current production. Here, a systematic, rigorously ordered, asymptotic derivation is given of nonlinear fluid equations for perturbations localized near a rational surface. We use the drift kinetic equation directly, assume plateau regime collisionality, and use a two-scale procedure for parallel gradients. We obtain several differences from previous works. First, the derivation here does not require frequencies to be less than the parallel ion flow equilibration rate; this is necessary for many modes of interest, and results in modifications of the perturbed bootstrap currents. Second, we notice that the neoclassical ion flows effect the perturbed pressure response. A linear analysis shows that this substantially modifies dynamics and stability for low and modest mode number perturbations with frequencies of order or less than the diamagnetic frequency, e.g., drift-tearing, drift-Alfvén, and bootstrap driven interchange-like modes. The systematically derived dissipative terms are also used to examine the nonlinear dynamics of resonant magnetic perturbations in stellarators when a non-ambipolar transport process is present.

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

A passive or very low frequency drift pumping scheme.*

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A passive or very low frequency pumping scheme is proposed for those ions trapped in the transition region of a throttle coil version of a tandem mirror, a region where the vacuum curvatures are relatively large. The mechanism requires effective control over the bias value of the plasma potential. The idea is simply to adjust the value of the radial electric field in the transition region to a very low value, where the resulting combination of $E \times B$ drifts and curvature drifts for the trapped particles will approximately cancel, leading to stalling orbits, $\dot{\theta} \rightarrow 0$, whereupon the relatively large geodesic curvature is effective in causing radial loss. In the rigid rotor limit, once the stalling condition is achieved it is maintained during the particle's radial excursion, and so loss then is direct convection rather than stochastic. In practice the $E \times B$ drift is not rigid rotor and we also need to range over the stalling conditions for a range of particle energies, so that a low frequency amplitude modulation of the bias potential is desired.

Here, the rf is not a fluctuating $m = 1$ or $m = 2$ B or ϕ as in previously proposed drift pumping schemes, but instead is an $m = 0$ ϕ being used to change the equilibrium orbits in a time dependent manner. The rf supplies no radial motion of its own, in contrast to the previous scheme where a 'sloshing' radial motion was an inherent feature. The mechanism can be thought of as a *zero* frequency resonance, despite the apparent need for time dependently scanning through a range of conditions. (There is another, but much less effective, passive loss channel due to bounce–drift resonance, when the potential is *not* biased to low values.)

Orbit calculations for the throttle coil version of TMX–U, when the potential is zero, or biased to a near zero value in the transition region, show radially unconfined orbits for ions deeply trapped in the transition region, i.e., with $KE_{\perp}/KE_{tot} \approx 0.7 - 1.0$, measured at the transition region midplane. Ions with a smaller pitch angle remain radially confined. It is necessary to bias the potential to a transition region midplane value $\phi_{Tr} \approx -100v$ to cause the stalling and radially unconfined orbits for ions less deeply trapped in the transition region—specifically for $KE_{tot} = 1.0kev$ the radially unconfined ions then are those near the loss boundary with $KE_{\perp} = 0.24 - 0.40kev$. This negative value of the potential in the transition region gives $\dot{\theta}_{E/B} > 0$ which then is able to cancel the negative $\dot{\theta}_{\nabla B}$, for this particular energy, pitch angle class of ions. For rigid rotor $\dot{\theta}_{E/B}$, the loss time, to move from near the axis out to the halo radius, is approximately $1msec$ for these $KE_{tot} = 1.0$ ions. The required low frequency amplitude modulation should be on the order of the $E \times B$ drift frequency corresponding to the transition region potential or $f \approx 10^3 sec^{-1}$.

This scheme also appears selective: even if some class of center cell passing ions encounters a stalling condition, they will not undergo large radial excursions due to the cancellations at opposite ends.

*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.

SHERWOOD THEORY MEETING

Transport Simulation Results from the FRC Transport Code for the IPSG Representative Discharges

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The Ignition Physics Study Group has provided a TFTR data set and a complete set of transport coefficients for benchmarking the various transport codes currently in use within the MFE community. They have also provided data sets from Alcator C, ASDEX, Doublet III, ISB-B and PDX for comparison. The goal of this work is to apply the benchmark transport coefficients to all of the data sets provided for a machine to machine comparison.

The transport coefficients to be used in the comparison are as follows:

I. Electron thermal diffusivity[1]

$$\chi_e = \chi_s \equiv 4.4 \rho_m R_m^{-2} n_{e20}^{-7/8}$$

II. Ion thermal diffusivity[2]

$$\chi_i = 0.2\chi_e + \chi_i^{CH}(Z_{eff}) + \text{Sawtooth Mixing Model}$$

III. Particle diffusion coefficient

$$D = 0.2 * \chi_e$$

IV. Conductivity[3]

$$\sigma = \sigma_0 \Lambda_E(Z_{eff}) \left(1 - \frac{f_T}{1 + \xi \nu_e^*}\right) \left(1 - \frac{c_R(Z_{eff}) f_T}{1 + \xi \nu_e^*}\right)$$

In order to facilitate the use of these data sets with other transport models, an MFE database has been created. This database is patterned after the one used for TEXT[4]. The commercial relational database package INGRES™ and many of the same tables, with slight modification, are used. Now, however, the database is built upon single discharges during which all diagnostics are taken.

Results from the transport simulations and comparisons between machines will be presented. The structure and implementation of the MFE database will also be discussed.

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* Supported by USDOE Contract No. DE-AS05-76ER 53193
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BALLOONING STABILITY OF TOKAMAKS WITH AN ISOTROPIC ALPHA DISTRIBUTION AND REALISTIC EQUILIBRIUM MODELS*

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ABSTRACT

Alpha populations can have a significant influence on the ballooning stability of ignition tokamaks. Using a deeply-trapped alpha model and the large aspect ratio shifted circular flux surface equilibrium, our previous calculations[1] have shown that the interaction of the kinetic ballooning mode with the alpha precessional drift can lower the first stability beta limit and close off the access normally present at low shear between first and second stable regions. Recently, a number of improvements have been made to increase the realism of these calculations. These include using improved equilibrium models and developing an approximate method for solving the integro-differential equations which result from use of an isotropic alpha distribution. We have used both a finite beta numerical equilibrium code as well as an improved analytic equilibrium model which includes sin2Θ terms in addition to the previously used lower order contributions. Preliminary results indicate that both of these modifications lead to non-negligible changes in stability properties. Comparisons of the different equilibrium models and the deeply-trapped versus isotropic distributions will be discussed for parameters of interest to ignition and breakeven tokamaks.

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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.

Alfvén Ion-Cyclotron Instability in Mirrors with Fanning Geometry

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The Alfvén ion-cyclotron (AIC) instability is an electromagnetic instability that propagates primarily along the magnetic field lines and is driven by the velocity anisotropy of a plasma with finite ion beta. In the fanning geometry of a mirror cell with a quadrupole field, a circular flux surface at the midplane becomes highly elliptical at the ends of the cell. A mode that goes to zero at the plasma edge therefore has a relatively large perpendicular wavenumber $k_\perp$ near the ends. This fact motivates a treatment of the AIC mode that includes finite $k_\perp$.

The general dispersion relation with finite $k_\perp$ is studied with two model ion distributions, a two-temperature Dory-Guest-Harris (DGH) distribution and a delta-function distribution in velocity. In both cases, we find from the local dispersion that the fundamental-AIC-mode growth rate decreases as the angle θ between $\mathbf{B}$ and $\mathbf{k}$ increases. If $\theta > 20°$, the second (or even the third) harmonic can be destabilized.

To take into account the nonuniformity along field lines, we subject the general local dispersion relation to WKB analysis. We use analytical and numerical methods developed previously.[1,2] Results will be reported.

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[*] Supported by U.S.D.O.E. contract DE-AC03-76-ET53057.

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THE ALPHA PARTICLE INDUCED FISHBONE MODE*

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Tokamaks designed to reach thermonuclear ignition will have significant populations of α-particles. The excitation of the fishbone mode[1] by the trapped component of the alphas is a distinct possibility. Thresholds for mode excitation and resonant loss of the trapped alphas are investigated for different ignition design parameters. Schemes for suppressing the instability and/or the resonant loss will also be explored.

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

IDEAL MHD STABILITY OF TFTR*

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In recent years several advanced tokamaks, i.e., PBX, PDX, ASDEX and DIII have entered an experimental regime, where finite β effects can be explored. The results of the experimental studies indicate the presence of an operational β limit, often referred to as the Troyon limit. Several theoretical studies have shown that this limit is not a hard limit but may be exceeded with appropriate choice of current profiles and boundary conditions. With the recent addition of neutral beams the TFTR tokamak is now in a position to enter the finite β regime. It is therefore appropriate to assess the consequences of finite β on its stability. TFTR differs from the other devices mentioned earlier, in its simpler, circular cross-section and the absence of a nearby separatrix. We use well defined methods to study the stability limits for both low and high-n toroidal mode numbers in TFTR geometry. We shall address the possibility of accessing the second region of stability as well as determining the β limits in the first region. We shall compare the latter with the Troyon limit.

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

TESTING TOKAMAK TRANSPORT MODELS BY PREDICTIVE SIMULATIONS

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Various models for flux-surface-averaged plasma transport in tokamaks are examined. Included are (1) theoretical models--based on first principles theories of plasma turbulence, (2) semiempirical models--containing adjustable parameters but derived from dimensional and other theoretical constraints, and (3) purely empirical models--based on observable plasma parameters with no explilcit theoretical constraints. The plasma transport coefficients in the models are either (1) derived from radially localized parameters or (2) contain global plasma parameters (either volume averages or central values). In many cases, computations based on gradual evolution of plasma parameters are interrupted by nearly instantaneous mixing events or other discontinuities. Examples are shown comparing predictions for various measurable quantities and profiles from various tokamaks. Emphasis is placed on semiempirical models with locally determined transport coefficients, with and without sawtooth mixing models. The advantages and disadvantages of different approaches to predictive transport modelling are reviewed.

TURBULENT RELAXATION TO A FORCE-FREE FIELD-REVERSED STATE

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The evolution of highly non-equilibrium initial conditions of an incompressible magnetohydrodynamic (MHD) Z pinch is described by a three-dimensional, pseudospectral numerical code. The one-fluid incompressible MHD equations are solved in a region which is periodic in the z-direction and is terminated by a smooth, square, rigid, perfectly-conducting boundary in the x and y (poloidal) directions. The magnetofluid is assumed to be resistive but non-viscous. The numerics are an outgrowth of a 3-D code[1,2] we have used to solve the Strauss equations of "reduced" MHD. A new and central feature of this fully three-dimensional code is that the boundary conditions are represented in a natural way by using the Turner-Christiansen functions[3] as a pseudospectral expansion basis.

Considerable MHD turbulence develops from broad-band noise non-equilibrium initial conditions. It has sometimes been thought that the achievement of turbulent selective decay to a field-reversed force-free state requires Lundquist numbers of the order of tens of thousands. However, we find the transitions possible, even in the absence of externally supplied electric fields, at values of S of only a few hundred. A force-free region in the interior of the plasma grows with time and achieves spontaneous reversal of the toroidal magnetic field at the wall. This field-reversed state is characterized by a larger aligned core region surrounded by a dwindling, but persistently active, turbulent boundary layer. The turbulence, the relaxation, and the force-free state are all aspects of a single process.

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SHERWOOD THEORY MEETING 1986

The Minimum Scaling Law of Tokamak*

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A model based on low frequency electromagnetic turbulence is solved by using renormalized perturbation theory to drive self-consistently a scaling law for anomalous electron transport in a tokamak plasma with auxiliary heating. It is basically the same as the result heuristically obtained by Ohkawa (1985). But, when the injected auxiliary power $P_{\rm inj}$ highly exceeds Ohmic heating power, we found that the self-consistent energy confinement time scaling becomes $\tau_E \sim P_{\rm inj}^{-1/3}$. The same procedure is also extended to the case where current drive and classical collision are included.

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

DYNAMOS, DISRUPTIONS, AND F-θ PUMPING*

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ABSTRACT

Tearing modes produce a relaxation of the current which can be described as a hyper-resistive term in Ohm's Law. It contains a fourth derivative of the magnetic helicity, while the resistive term has a second derivative. The hyper-resistivity D has been found quasi-linearly for the mean field Ohm's Law.[1] It is calculated using the direct interaction approximation to obtain the renormalized Ohm's Law governing the tearing modes. It appears to be more important than the turbulent resistivity in determining the growth rates of the modes. Hyper-resistivity must therefore be taken into account in understanding tokamak disruptions. It may also provide a useful subgrid scale numerical model for computation.

F-θ pumping,[2] a low frequency current drive scheme for RFP's, is simulated in 1-D computations with hyper-resistivity D in Ohm's Law. We verify that it is possible to maintain a positive, though time varying, toroidal current, without a net toroidal voltage. This requires D sufficiently larger than ηa^2, where η is the resistivity and a the minor radius. Otherwise, the toroidal current periodically reverses sign.

Although hyper-resistivity is said to produce a dynamo effect in RFP's, it is actually an anomalous dissipation mechanism. A resonant fast dynamo effect has been found, assuming a mean toroidal magnetic field and velocity, when kinetic energy is large compared to magnetic energy. Unlike dynamos described by Moffatt,[3] the resonant toroidal fast dynamo persists in the limit of infinitesimal resistivity, which is the case in the solar dynamo.

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*This work was supported by U.S. Department of Energy Grant No. DE-FG02-86ER53223.

SHERWOOD THEORY MEETING 1986

Scrape-off Layer Fluctuations and Transport including Limiter and Radiation Effects*

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Large density and potential fluctuations (10–50%) have been experimentally observed in the scrape-off layer (SOL) plasma.[1,2] Some prevalent edge turbulence characteristics found are: moderate poloidal mode numbers dominate ($m \approx 5 - 20$); radial correlation lengths are smaller than poloidal ones; and fluctuations are non-adiabatic. These characteristics indicate that drift wave turbulence models are not appropriate for the SOL region.

We present an analysis of SOL fluctuations using a rippling mode or resistivity gradient driven turbulence[3] calculation. This accounts for the cold and highly collisional regime found in the SOL and insures consistency with the aforementioned edge turbulence characteristics. The paramount boundary condition effects due to inclusion of the limiter are incorporated throughout the analysis. In particular, the line-tying effects caused by a simple conducting poloidal limiter can lead to an order of magnitude reduction in rippling mode growth rate in the SOL region.[4] Theoretical predictions of saturation amplitudes and transport are presented and compared to experimental results.

Other effects can also be pertinent to the study of edge turbulence. Recently, multifaceted asymmetric radiation from the edge (MARFE)[5] has been observed in tokamaks. The MARFE phenomenon results in a source of radiation, about 20% of the ohmic power, from the SOL region. Thus, it is important to incorporate radiation effects in an edge turbulence calculation since this radiation can substantially affect fluctuation dynamics. In this light, we analyze SOL fluctuations including the radiation effect. Radiation is taken into account as a radiative cooling term in the resistivity equation which results in additional drive for the rippling mode.

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* Work supported by USDOE Contract #DE-FG05-80ET-53088.

SHAPE CONTROL OF ELONGATED TOKAMAKS*

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We demonstrate the feasibility of maintaining shape and position control of a high elongation K ≈ 2.5 tokamak over times long compared to the field diffusion and transport time scales. We show that each of the lowest shape harmonics of the plasma-vacuum interface can be controlled through a relatively simple set of external coils using active feedback on flux loop sensors. This control is verified by numerical simulations where the shape of the interface remains fixed as the plasma pressure increases and the current redistributes. The simulation code, TSC,[1] is verified by detailed comparison with magnetics data from PBX. We also discuss recent changes in the numerical methods used in TSC where the multiple time scales associated with fast wave propagation and diffusion in the high resistivity vacuum are treated using fractional time step methods.

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

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Beta-Limit, Current-Disruption, and Profile Consistency*

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An important criterion for major disruptions caused by either high-beta or high-current in tokamaks is the edge current density gradient $\frac{1}{L_J} \equiv \frac{-a^3}{I}\frac{\partial J}{\partial R}$. This is revealed in a series of MHD simulations and also confirmed by equilibrium analyses of disrupted D-III discharges. With the pressure and the current density profiles linked by $J \propto p^{3/2}$, our simulations not only reproduce the Troyon beta-limit[1] ($C \equiv \beta_T aB/I \approx 2.8$) but also provide the optimum profile broadness parameters for a wide range of safety factor values q_a/q_0 in the experimental range of PDX and TFTR. Near the beta-limit, the important feature is the similar magnitude of the normalized edge current density gradient for the various q_a/q_0-values. For the D-III discharges, disruptions occur as the edge current scale length is reduced to reach a threshold value. The monotonic decrease in time of the edge scale length is observed in diverted and limited shots as the discharges approach the disruption time. For most disrupted cases with neutral beam heating, this edge current scale length is $L_J^{-1} \simeq 2.0$ to 4.0 in agreement with our simulation results. The location for the largest gradient in the equilibrium quantity is generally associated with the largest perturbation (seen in simulations), thus making easier the interaction of the plasma edge region with the outside. The details[2] of the simulations and the D-III analyses will be presented. The MHD aspects of the profile consistency principle are also examined. The plasma profiles resulting from tearing mode stability indicate[3] that the tokamak energy confinement time τ_E increases linearly with the increase in the edge current density gradient. When the role of the tearing modes is ignored, the effect is very small. A large current pedestal, thus, enhances τ_E through internal profile modification by tearing modes, while it is harmful (to ideal external kink modes) from the disruption point of view. These conflicting effects are also observed in D-III experiments. The analysis including the localized ballooning modes together with the tearing modes shows results in variance with experimental observations. The global MHD stability calculations via a new initial value code CART[4] will be also presented including the usually[1] ignored effects such as those of magnetic separatrices, high elongation, and pedestal. For example, a separatrix itself is found[4] to have a very weak effect on both resistive tearing and ideal external kink modes if the same profiles are used.

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

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VORTEX SOLUTIONS IN DRIFTWAVE TURBULENCE

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Numerical solutions of mode-coupling equations show large scale long lived structures which can be interpreted as monopolar and dipolar drift vortices. In this paper we discuss basic models for vortex structures, in the electrostatic limit as well as for finite-ß plasmas. It is shown that the various scalings result in different stationary states. The linear stability of the latter are discussed, including the convection cells and the Hasegawa-Mima vortices. The problem of nonlinear stability as well as the influence of perturbations along B are also discussed. Finally, simple scenarios for excitation of vortices by the drift wave instability are proposed.

LBL-21165a

Sherwood Theory Conference, April 14-16, 1986, New York City

Covariant Variational Approach to Electromagnetic Wave Propagation: Maslov Transforms, Polarization Transport, and Angular Momentum*

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The quadratic action functional

$$S(A) = \int d^4x_1 \int d^4x_2\, A_\mu(x_1)\, A_\nu(x_2)\, \varepsilon^{\mu\nu}(x_1,x_2)$$

can be expressed as a covariant phase-space integral[1]

$$S = \int d^4k \int d^4x\, \underset{\sim}{A}^2(k,x) : \underset{\sim}{\varepsilon}(k,x).$$

For an eikonal wave in the x-representation:

$$A_\mu(x) = a(x)\, e_\mu(x) \exp i\theta(x) + \text{c.c.},$$

the action is expanded to first-order in the eikonal parameter. Variation of S yields a closed set of coupled covariant equations for the transport of phase θ, amplitude a, and polarization e. In particular, the polarization transport involves the Poisson bracket $\{e^*,e\}$ of the dielectric eigenvector $e(k,x)$. The k-representation is obtained by inspection, from the symmetry of S; thus caustic singularities are easily avoided. The Noether algorithm yields the intrinsic wave angular-momentum density. Conservation of angular momentum in wave interactions produces selection rules for wave decay.

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*This research was supported by the Office of Fusion Energy and the Office of Basic Energy Sciences of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

THE MODE CONVERSION- TUNNELING EQUATION IN THE PARAXIAL PROPAGATION LIMIT*

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Fast magnetosonic wave heating of tokamak plasmas involves the focussing of a launched wavefront, with a finite extent in the poloidal direction, on to the mode conversion-absorption layer, located near the magnetic axis of the discharge. In order to study diffraction effects associated with the finite transverse extent of the wavefront as it propagates through the layer, the mode conversion-tunneling equation has been reformulated by applying the parabolic approximation method[1] to the linearized Vlasov-Maxwell system of equations, which determines the wave structure within the layer. This approximation is valid in the paraxial propagation limit, in which the wavefront propagates at near-normal incidence to the layer and varies more rapidly in the direction of propagation than in the transverse direction. The plasma model considered consists of a uniform density, uniform temperature slab region in which the equilibrium magnetic field is oriented in the $\hat{z}$-direction and varies linearly in the $\hat{x}$-direction. An equivalent dielectric tensor is derived by solving Vlasov's equation for the perturbed particle distribution functions and computing the perturbed currents flowing in the plasma due to the presence of the wave fields. The generalized form of the mode conversion-tunneling equation in then derived from Maxwell's equation using the approximation that the transverse derivatives of the wave fields are small in comparison to the derivatives of the field in the $\hat{x}$-direction, the primary direction of propagation. Properties of the resulting equations and their solutions will be discussed.

*Work supported by US DOE Contract #DE-AC02-76-CHO-3073.

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SHERWOOD THEORY MEETING 1986

Destabilization of Alfvén-Resonant Modes by Resistivity and Diamagnetic Drifts*

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The resistive drift-Alfvén modes have previously been thought to be stable. By carefully including in our model the radial variations in the diamagnetic drift frequency, we demonstrate both analytically and numerically the existence of *unstable* resistive drift-Alfvén modes. The salient features of this new mode are as follows:

(1) The mode is resonant at the drift-Alfvén surface where $\omega^2 \simeq \omega_{*e}^2 \simeq k_{\|}^2 v_A^2 \big/ \left(1 + T_i/T_e\right)$.

(2) It is destabilized by radial gradients in the electron diamagnetic drift frequency ω_{*e}.

(3) The growth rate has only a weak dependence on η : $\gamma^4 \sim \omega_{*e}\omega_{*e}'\eta/k_{\|}'$.

(4) The mode is *not* Δ'-driven; it is unstable even when the purely resistive mode is stable ($\Delta' < 0$).

(5) The parallel electric field vanishes outside the resonance layer; thus, the flux function $\psi = 0$ at the mode rational surface where $k_{\|} = 0$.

These modes will be discussed in terms of their effect on the nonlinear evolution of the $m = 1$ resistive tearing mode in tokamaks. In contrast to the purely resistive mode where only $m/n = 1/1$, and possibly $m/n = 2/2$ modes are linearly unstable, all harmonics are unstable for the Alfvén-resonant mode. Their effects on the saw-tooth oscillations, in particular on the crash-times, will be examined.

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

SHERWOOD THEORY MEETING 1986

Interaction of Electrostatic Drift Holes and Normal Modes in a Plasma*

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Three-dimensional localized phase space density holes have previously been shown to exist in an inhomogeneous plasma.[1] Both the structure and dynamics of electrostatic drift holes have been determined in the case where coupling to collective resonances (waves) is not considered. Here, the interaction of electrostatic drift holes and electron drift waves is studied by allowing the hole Doppler frequency to be resonant with the normal modes of the background plasma. Physically, wave–hole coupling affects the hole energy by altering the dielectric response of the medium and by permitting resonant exchange of energy between waves and holes. Because hole structure represents a maximum entropy configuration for set energy and mass, such changes can modify hole structure. For a hole whose phase space volume is box-shaped, it is shown that the hole potential is no longer localized radially as it is in the uncoupled case, but oscillates with an envelope decaying as $x^{-1/2}$. The extent to which characteristic hole scales are changed by hole–wave coupling is shown to depend on both the wave amplitude and the degree of particle trapping in the self potential. For holes whose trapped particle population is deeply trapped in the self potential, the characteristic scales of hole structure are not significantly altered. Hole dynamics is affected by Cerenkov emission into the waves. For deeply-trapped holes, a test-hole approximation yields a formula for the hole growth rate which reduces to previous results[1] when wave–hole coupling vanishes. Preliminary simulation results are also presented.[2]

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2. R. D. Sydora, J. N. Leboeuf, T. S. Hahm, and P. H. Diamond, Bull. Amer. Phys. Soc. **30**, 1397 (1985).

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

MHD EQUILIBRIUM AND STABILITY CODE WITH GENERAL TOPOLOGY

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We have undertaken to extend our 3D equilibrium and stability code to solutions with surfaces that are not nested and to domains which are not starlike. Our intention is to enhance resolution and to obtain a rapidly convergent algorithm while preserving all the previous capabilities of the code, including nonlinear stability and the Mercier criterion. Major issues are convergence and resolution at the magnetic axis, convergence of the iteration procedure to residuals of the order of the roundoff error, and nonuniqueness of the magnetic field representation.

As a first step, a 2D code has been developed and implemented which solves these problems, in a fashion that generalizes to the 3D problem. The magnetic field is expressed as a sum of cross products that allows for solutions with islands, and a spectral representation results in enhanced resolution. Our iterative procedure converges rapidly to the roundoff error limit, so that the energy can be computed to seventh or eighth digit accuracy as required for nonlinear stability calculations. The topology of the flux surfaces can be prescribed or it can be obtained from energy minimization. A mapping of physical space onto an auxiliary domain removes the starlike limitation. All these properties are exhibited through computed examples.

DOE/ER/53223-10

3-D ALTERNATING DIMENSION ENERGY DISSIPATION SIMULATION IN A TOKAMAK*

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ABSTRACT

A 3-D Alternating Dimension transport code is used to simulate the dissipation of a delta function energy pulse placed in the interior of the plasma in a tokamak. The energy pulse is released in the interior of a plasma which is in a steady state configuration. The time for the pulse to diffuse to a given fraction of its original strength is monitored and an energy relaxation time constant is calculated. This relaxation time is compared to the relaxation of a global perturbation. This numerical experiment also has application to plasma pellet injection studies.

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*This work was partially supported by U.S. Department of Energy Grant No. DE-FG02-86ER53223.

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NONLINEAR BEHAVIOR OF ELECTROSTATIC PLASMA WAVES

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ABSTRACT

We present an analytic theory for evaluating the long time behavior of single mode nonlinear electrostatic plasma waves based on Vlasov equation with Fokker-Planck collision terms. The dynamics of the resonant electrons (electrons moving slowly relative to the wave train) is highly nonlinear for $\nu << A^{3/2}$ where ν is the electron collision frequency and A the wave amplitude.

Although nonlinearity dominates the dynamics of resonant electrons for $\nu << A^{3/2}$, collisional effects are also important in that as higher order terms, they determine the lowest order distribution function. Furthermore, collisional effects provide a smooth transition between the untrapped electrons and the trapped electrons through a thin layer across the separatrix in the velocity space island structure that can be solved by Wiener-Hopf technique.

The long time evolution of the wave amplitude A(t) is given by $dA/dt = \nu(\beta A^{-1/2} - \alpha A)$ where α and β are positive constants; the β-term arises from a redistribution of space charge of the resonant electrons by collisions while the α-terms comes from the collisional effects on the thermal bulk electrons. Slow change in the background Maxwellian, wave heating, current generation and quasi-steady state are also described.

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*This work was supported by U.S. Department of Energy Grant No. DE-FG02-86ER53223.

Transport in a Toroidally Rotating Tokamak*

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A gyrokinetic formulation permitting toroidal rotation speeds on the order of the ion thermal speed is presented which retains the classical, neoclassical, and induced electric field contributions to tokamak transport. The neoclassical contributions are of two distinct types: (i) implicit and (ii) explicit. To evaluate the implicit contributions a gyrophase independent reduced kinetic equation must be derived and solved to obtain the implicit portion of the distribution function. This kinetic equation is derived to the requisite order in a gyroradius over scale length expansion, ρ/ℓ, by removing the gyrophase dependence order by order in ρ/ℓ. The explicit contributions are generated by portions of the distribution function which are explicitly determined by the gyrokinetic procedure and are independent of the regime of collisionality. These explicit terms arise because of gyromotion, but are neoclassical since they vanish in a straight, constant magnetic field. Their contributions to the radial fluxes are formally the same order in ρ/ℓ as the classical and implicit neoclassical terms; however, auxilliary expansions often make them small.

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*Work supported by U.S. Department of Energy contracts DE-AC02-77-ET53053 (Yale) and DE-AC03-76-ET53057 (SAIC).

GAS BREAKDOWN BY SECOND HARMONIC ECH*

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ABSTRACT

Microwaves with frequency twice that of the electron cyclotron frequency have been used to break down neutral gas in devices such as the Heliotron-E stellarator.[1] The linear absorption at the second harmonic is proportional to $(\text{gyroradius})^2$ which approaches zero for cold electrons; however, the nonlinear interaction of second harmonic waves with cold electrons is very large when the resonance is precisely tuned to nearly uniform regions of magnetic field strength.[2] In this case, electric field strengths on the order of 100 volts/cm cause energy excursions which take cold (~0.025 eV) electrons to several hundred eV if collisional processes do not strongly interfere.

A few free electrons always exist in a confinement device due to natural background radiation, and ionization of neutral particles can result when this small class of electrons interact with the second harmonic wave in a nonlinear way. Models are presented to demonstrate how these nonlinear interactions could lead to gas break down, and results are compared with experimental observations.

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

Analytic Calculation of Neutral Penetration into a plasma *

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For central-cell densities typical of present tandem mirrors, only a few generations of neutrals are important in determining neutral densities. This enables analytic calculation of neutral density in such devices. We present analytic formulae for neutral densities in slab and cylindrical plasmas, starting from molecular breakup and continuing for several generations. These calculations allow the verification of Monte Carlo gas penetration codes. They are also useful as replacements for the crude "back of the envelope" models used in present tandem mirror modelling codes. Useful and accurate approximations to the neutral density may be made if the range of one generation is substantially shorter than that of the next generation — as is the case for atoms born by breakup of room temperature molecules. For example, in a slab, the density of such atoms (the "Franck-Condons") falls off with distance z from the edge as $exp(-z/l_{FC})/z$ where l_{FC} is the mean free path of the Franck-Condons. In a cylinder the corresponding result is $exp(-z/l_{FC})/\sqrt{z}$. Comparison of the analytic results with the DEGAS code of Heifetz et. al. [1] will be presented.

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* Work performed for U.S.D.O.E. by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

[1] J. Comp. Phys. **46**, 309 (1982)

OPTIMIZED FORMATION OF RELATIVISTIC-ELECTRON PLASMAS IN TOKAMAKS USING MULTIPLE-FREQUENCY ELECTRON CYCLOTRON HEATING

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ABSTRACT

The relativistic-electron plasmas resulting from electron cyclotron heating in magnetic mirror plasma-confinement configurations are now well established,[1] and interest is growing in the application of these plasmas to tokamaks[2] and heliacs.[3] Efficient production of relativistic-electron plasmas in tokamaks and heliacs requires the resolution of a number of issues that were not critical in typical magnetic-mirror devices. For example, the effective mirror ratio in tokamaks, $M \sim 1 + 2r/R$, is generally less than 2, leading to the occurrence of relativistic heating gaps; i.e., energy intervals in which the electron heating rate vanishes because of the relativistic decrease in the electron gyrofrequency. Using a fully relativistic, one-dimensional, Fokker-Planck model of the electron cyclotron heating kinetics (FPECH),[4] we have demonstrated that these gaps effectively prevent the formation of a relativistic-electron plasma. The gaps can be bridged by illuminating the plasma with microwave power at several different frequencies, corresponding to overtones of the relativistic-electron gyrofrequency. We describe the distribution of relativistic electrons in energy predicted by the FPECH model when the frequencies and relative power densities in the different sources are selected for optimal formation of relativistic-electron plasmas in typical tokamaks.

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SHERWOOD THEORY MEETING 1986

Electron Diffusion in Tokamaks Due to Electromagnetic Fluctuation*

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Calculations for the stochastic motion of electrons due to a spectrum of electromagnetic drift wave fluctuations are presented for a simple, local model of the tokamak plasma. The dependence of the diffusion coefficient on the amplitude, phase velocity and spectral index m of the fluctuation spectrum $k_{\min} \leq k_\perp \leq k_{\max}$ is studied. The wavenumber spectrum is taken to be a low order (5×5) randomly-phased, isotropic, monotonic spectrum with a power law decrease $\phi_{\mathbf{k}} = \phi_1/k^m$ with $1 \leq m \leq 3$. An Ohm's law is used to relate the vector $A_{||}$ and scalar φ potentials. The degree to which the diffusion coefficient is weakly dependent on the spectrum parameters is investigated. The scaling of the diffusion is shown to vary as $\varepsilon^{1/2}\left(\rho_s/r_n\right)\left(cT_e/eB\right)$ for density $n < n_c$ and as $\varepsilon^{1/2}\omega_{be}\left(c^2/\omega_{pe}^2\right)$ for $n > n_c$. The work is carried out in collaboration with P. Yushmanov and V. Parail.

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

EXCITATION OF ION BERNSTEIN WAVES IN A NONUNIFORM PLASMA*

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A second order differential equation has been derived through a systematic expansion of the exact integro-differential Poisson equation, which correctly includes the effect of diamagnetic drifts on the propagation of Ion Bernstein waves (IBW). The zero order equilibrium consists of a uniformly magnetized plasma slab having a Gaussian density profile in the x direction (⊥ to $\mathbf{B}_0$) and a Maxwellian velocity distribution function. The differential equation is Fourier transformed in y (⊥ to x) and z (∥ to $\underset{\sim}{B}_0$) and solved numerically to obtain the IBW waveforms and to calculate an antenna loading impedance. Multiple ion species can be included in the model. The k_y and k_z of the excited waves are fixed by the antenna. The IBW solutions demonstrate a density dependent cutoff to propatation in x where the local Debye wavenumber becomes comparable to k_y. Reflection of the wave from this density cutoff on the side of the plasma opposite the antenna is also observed. Since the density at which an IBW mode becomes evanescent depends on the k_y of the mode, the plasma density profile effectively filters out the high k_y components of the antenna spectrum. The local diamagnetic drift also introduces an asymmetry into the coupling based on the sign of k_y. IBW waveforms and antenna loading results from driving frequencies around second order ion harmonic will be presented.

* Supported by USDOE.

NEOCLASSICAL TRANSPORT IN BEAN-SHAPED TOKAMAK PLASMAS*

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In a bean-shaped tokamak plasma, such as can be created in the Princeton PBX device, particles can be magnetically trapped on the inside of the torus (small major radius R) as well as on the outside (large major radius). The question then arises whether the usual expressions for neoclassical tokamak transport properties, given, for example, by Hirshman and Sigmar [Nucl. Fusion 21, 1079 (1981)], which are derived for particles trapped in only one well, apply in this case also. In particular, the banana regime properties, which depend directly on the fraction of trapped particles f_t, are of interest.

We use the DKES code (S. P. Hirshman et al., submitted to The Physics of Fluids) to numerically evaluate banana regime transport properties for bean-shaped plasmas described by a model magnetic field. We have previously calibrated the numerical results from the DKES code against the Hirshman-Sigmar expressions over a large range of tokamak aspect ratios for plasmas with particles trapped only on the outside of the torus [Bull. Am. Phys. Soc. 30, 1425 (1985)]. Here we find that the Hirshman-Sigmar expressions are in excellent agreement with the numerical results for the bean-shaped plasmas when we calculate $f_t = 1 - f_c$ and evaluate f_c, the fraction of circulating particles, from the usual integral over the pitch-angle variable $\lambda = \mu/E$. In that integral, $\lambda_{crit} = 1/B_{max}$, where B_{max} is the global maximum of B.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

ION AND ELECTRON CONVECTIVE LOSSES DUE TO POLOIDAL ELECTROSTATIC FIELDS IN TOROIDAL DEVICES*

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Poloidal variation of the electrostatic potential in toroidal devices can lead to significantly increased particle losses. This is particularly true for low energy particles which do not experience the confining effects of rotational transform (e.g. trapped particles in tokamaks or stellarators). The basic phenomena causing these losses involve scattering from one drift orbit to another. For cool particles, which tend to follow potential surfaces, energy scattering allows particles to cross the potential surfaces -- particularly near points where the electrostatic potential is low. In some cases the excursions of the orbits are sufficiently large that convection rather than the slower diffusive losses occur. To illustrate this point we have used Monte Carlo techniques to calculate loss rates for ions and electrons in EBT. We find that for electrostatic potentials similar to those observed in EBT, both ions and cool electron life times are comparable to those obtained experimentally. The new ion results are interesting because they show a "plateau" in the (mostly convective) losses as a function of collisionality. This suggests that analytic approximations based on a random phase approximation might prove useful.

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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.

SHERWOOD THEORY MEETING 1986

Computer Simulations of Ion-Temperature-Gradient-Driven Turbulence*

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Ion-temperature-gradient-driven turbulence, which evolves from unstable ion-temperature-gradient modes (η_i modes, where $\eta_i = d\ln T_i/d\ln n$) has been proposed as a possible explanation of anomalous heat conduction observed in recent tokamak experiments. Lee and Diamond[1] have investigated this phenomenon theoretically. Renormalized spectrum equations have been derived and solved in order to obtain the spectra of stationary η_i-mode turbulence. The resulting anomalous heat diffusivity which is derived is consistent with experimentally-deduced diffusivities.

We are investigating scalings of the underlying saturation level of η_i-mode turbulence in a sheared magnetic field by particle simulations in $2\frac{1}{2}$-D and 3-D. A slab representation is used. The codes are standard electrostatic particle codes with full dynamics ions. The electrons are either treated as Boltzmann electrons for pure η_i modes or in the guiding center approximation when electron temperature gradients and electron–ion collisions are desired. The scaling of the measured saturation levels with η_i and shear strength (L_s) are in qualitative agreement with theoretical predictions. More detailed comparisons with theory are in progress.

Reference

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

NONLOCAL RESISTIVITY AND THE KINETIC DYNAMO IN THE REVERSED FIELD PINCH*

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The kinetic dynamo theory (KDT)[1] uses magnetic field line stochasticity and the long mean free path of fast electrons to explain the sustainment of field reversal in a reversed field pinch (RFP). In the original formulation of the KDT, it was presented in slab geometry with no ambipolar fields. It has now been developed in cylindrical geometry with consideration of a radial electric field. The relationship between the KDT diffusion term and the Boltzmann equation will be discussed. The effects of field-line and particle-orbit stochasticity on transport of plasma and energy will be examined. It is noted that stochastic diffusion counteracts the inward $\underset{\sim}{E}\times\underset{\sim}{B}$ compression of a driven RFP.

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*Work performed under the auspices of the USDOE.

MHD MODEL WITH THE HALL TERM*

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We have been studying MHD models with the inclusion of the Hall term in the Ohm's law for some time now. This method enriches the physics contained in the MHD calculations of the fusion plasmas by predicting many more wave modes, such as magnetoacoustic, Alfven, ion cyclotron, and whistler waves. In that connection, we developed 2 and 3 dimensional models for studying infinite plasmas and the wave propagations in them. Simulation results were compared with the theoretical dispersion relations for arbitrary angles of propagation and showed excellent agreement. Recently we have generalized the earlier studies to include kinetic ion rather than fluid elements, and were able to observe Bernstein waves. Theoretical dispersion relations for most cases have been developed and show good agreement with the simulation results. These wave studies demonstrate how the model reproduces a wide variety of modes which would not have shown up in simple MHD.

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*Work supported by USDOE and NSF.

A 3D MHD EQUILIBRIUM CODE THAT DOES NOT ASSUME THE EXISTENCE OF GOOD FLUX SURFACES*

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We have developed a three-dimensional MHD equilibrium code that is capable of describing magnetic islands and stochastic magnetic field lines. The code updates the magnetic field at each step by solving a magnetic differential equation for the pressure driven current in the current magnetic field, and then solving Ampere's law in three dimensions. To accurately solve the magnetic differential equation we construct a coordinate system which nearly coincides with the good flux surfaces, and which interpolates through the islands and stochastic regions. We have developed algorithms which: (1) determine the location of the islands and stochastic regions and (2) use a Fourier decomposition along field lines in the regions of good flux surfaces to construct the required coordinate system. We describe these algorithms, and demonstrate their application to model fields. We also describe a recent modification of the code to improve the accuracy with which the boundary condition is imposed in solving Ampere's law.

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

1986 SHERWOOD THEORY CONFERENCE
April 14-16, 1986; New York, New York

ENHANCEMENT OF THE PARALLEL WAVENUMBERS ON THE MODE-CONVERTED ION-BERNSTEIN ICRF WAVES*

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It is known that the fast wave component of the ICRF wave undergoes mode conversion to the ion-Bernstein wave (IBW) in a tokamak at the point where the frequency of the wave is equal to the ion-cyclotron frequency, ω_{ci}, or $2\omega_{ci}$ [1]. The perpendicular (to the magnetic field, $\vec{B}_0$) wave-number ($k_\perp$) for this mode-converted branch increases rapidly as a function of distance away from the point of mode conversion. While the approximations of geometrical optics may not, in general, be valid for the externally launched fast wave, they become applicable for the IBW due to their large $k_\perp$. We have carried out a ray trajectory analysis in toroidal geometry with shear for a simplified dispersion relation that approximately describes the IBW [2]. We found that $k_{\|}$ (the wave-number component parallel to $\vec{B}_0$) along the IBW rays is significantly enhanced as they propagate away from the mode conversion region. This could help explain the strong electron heating observed during ICRF heating of tokamak plasmas. We will present detailed ray trajectory analysis for the exact dispersion relation that describes the IBW. The implications as far as electron heating are concerned will be discussed.

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* This work was supported by DOE Contract No. DE-AC02-78ET-51013.

Taking Advantage of Parallelism on the Cray Multiprocessors - A Question and Answer Session*

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The Computational Physics Group of the National MFE Computer Center has been engaged in an effort to develop efficient techniques for the solution of large-scale computational physics problems in a multitasking environment. This work has been on an algorithmic and a programmatic level. Areas of research have included:

(a) The development of sparse matrix solvers relevant to 2-D and 3-D systems of equations,
(b) The use of a three-dimensional plasma physics code as a test-bed for multitasking techniques,
(c) The development of a three-dimensional particle code.

Members of the Computational Physics Group will be available to answer questions and offer advise regarding the efficient utilization of the latest Cray machines.

*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.

EFFECT OF COLLISIONS ON THE TRAPPED PARTICLE MODES IN THE COLUMBIA LINEAR MACHINE*

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In the Columbia Linear Machine, there are four populations of particles: trapped electrons and ions, and loss electrons and ions. There are no passing populations as in Tandem Mirrors. Because of the Boltzmann response of the significant population (15%-40%) of loss particles, the growth rate of the collisionless mode is reduced from the MHD rate by a significant factor. The effect of weak electron collisionality on this mode is studied using a Lorentz collision operator which is quite appropriate in the absence of an electrostatic barrier in this machine. With the above collision operator a bounce averaged drift kinetic equation yields a solution in terms of generalized Legendre functions of order zero/1/. In the low collisionality regime, this result leads to a small stabilizing effect ($\sqrt{\nu_e}$) on the unstable collisionless trapped particle mode, where ν_e is the electron collision frequency. This effect is the inverse analog of the destabilization of a marginally stable collisionless mode found before/1,2/. For intermediate collisionality, the drift mode is strongly destabilized as found before/1,2/. Comparison with the results using a Krook collision operator indicates a strong qualitative difference in the weak collisionality case, but not in the case of intermediate collisionality. However, the quantitative differences are always small.

* Research supported by US DOE grant FG02-84ER53182

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Temperature Anisotropy Driven Low Frequency Instabilities in Homogeneous Plasmas

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A theory of low frequency (lower than ion cyclotron) modes in homogeneous plasmas with temperature anisotropies ($T_{\perp} > T_{||}$, with directions measured with respect to the magnetic field) is presented. From the analysis of a kinetic dispersion relation, containing all the wave-particle resonances (Landau and transit-time damping) and retaining an arbitrary electron to ion temperature ratio, it is found that the mirror ($T_e \rightarrow 0$, Hasegawa [1969]) and field swelling $T_i \rightarrow 0$, Basu and Coppi [1982]) modes are smoothly connected through the point $T_e = T_i$. In fact, only one unstable mode is ever present for a particular value of T_e/T_i and, thus, the two modes are manifestations of a single instability driven by either or both temperature anisotropies (electron and/or ion). A variation of T_e/T_i over five orders of magnitude results in changes in the growth rate of at most one order of magnitude. Thus an anisotropic plasma will always relax via one of these instabilities (as well as through the field aligned ion cyclotron instabilities) for any value of T_e/T_i, provided electron and/or ion temperature anisotropies exceed the required thresholds, determined in the $T_e = 0$ or $T_i = 0$ limits. This broadens the applicability of this mechanism for producing low frequency waves in space and laboratory plasmas since a cold species is no longer essential for plasmas with little or no spatial gradients ($\nabla P_o = 0$).

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INHOMOGENITY AND THE NONLOCAL CHARACTER OF TURBULENT PLASMA TRANSPORT[1]

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The equations describing the evolution of fluid quantities can be written as continuity relations. Boundary conditions are therefore crucial in determining fluxes of particles and energy through a stationary, inhomogeneous plasma. In particular, turbulent fluxes in the core plasma must be continuous with collisional transport at the outer plasma boundary, where gradients are known to be large but turbulent transport is small. Because of continuity, the relation between transport and equilibrium quantities must be nonlocal in nature. In particular, a boundary layer structure may determine the level of flux. To substantiate these notions, we have begun a systematic study of inhomogeneous plasma turbulence. Here, we treat a simple model for edge fluctuations in a magnetically confined plasma, based on the collisional drift instability. The particle flux can be estimated by use of a mixing-length argument, but one must be careful to take into account the role of the inhomogeneity of the turbulence near the edge, and to choose a mixing length which reflects the part of the turbulence spectrum which is most effective in transport; the effective mixing length varies, depending upon the dominant physics at a given location. Using bifurcation theory, we find asymptotically valid scaling laws, which we adapt to the inhomogeneous mixing length treatment of our model in order to obtain quantitative estimates of fluxes and turbulence levels. We compare these estimates with limits on the flux determined *via* the bounding theory of turbulent transport. Finally, we examine the prospects for extending this approach to more realistic models of the tokamak edge.

[1]Work supported by U.S. Department of Energy Contract No. DE–ACO2–76–CHO–3073

RADIAL DIFFUSION OF PLASMA CURRENT DUE TO SECONDARY EMISSION OF ELECTROSTATIC WAVES BY TAIL ELECTRONS

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As part of an overall program to study RF current drive, a collaborative series of simulations has been undertaken to examine wave-enhanced spatial diffusion of RF generated current profiles. In the work presented here, a 2-1/2 dimensional, electrostatic particle simulation code is used, which is periodic in one dimension and bounded in the other.[1] An initial current channel is set up in the plasma interior, having a square profile in the bounded direction. The current is initially carried by a long tail in the electron velocity distribution along the magnetic field, and containing about 10% of the total electron density.

As time proceeds, the current profile in space widens, and decays temporally. However, there is no particle diffusion in this geometry, because all the drifts (e.g., E x B) are in the ignorable direction. Therefore, this current diffusion can only come from spontaneous wave activity. Indeed, the frequency spectrum shows that waves with parallel phase velocities corresponding to particle velocities in the non-Maxwellian tail of the distribution are enhanced 3 - 4 times above the thermal fluctuation level. These waves propagate out of the initial current channel and can be absorbed by particles in other regions, resulting in a broadening of the current profile.

The current decay is due to electron-ion collisions, which transfer momentum to the ions. (Momentum of the system is conserved to 1 part in 10^7).

The initial "slideaway" velocity distribution inside the original current channel is found to relax to a half-Maxwellian (the velocity distribution with $v < 0$ remains Maxwellian with the original temperature). Outside the original current channel, the initial Maxwellian first develops a long tail, and later relaxes to a half-Maxwellian.

This simulation shows the importance of current diffusion due to spontaneous wave activity since particle diffusion is not occuring.

Work supported by USDOE and JIFT.

[1] V. K. Decyk, G. J. Morales and J. M. Dawson, Proc. of the 2nd Joint Grenoble-Varenna International Symposium on Heating in Toroidal Plasmas, Como, Italy, 1980, Vol. 1, p. 365.

DIFFERENTIAL RENORMALIZATION GROUP EQUATION FOR ALFVEN WAVE TURBULENCE

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Turbulence in the model Alfven problem of Chen & Mahajan[1] *is considered. The nonlinear coupling ensures the excitation of such high k-modes that one reaches unresolvable spatial scales. Renormalization Group theory will transform away the effect of these small scale structures on the large scale motion by introducing renormalized response functions. Invoking the inertial range* k^{-2} *spectrum found numerically by Chen & Mahajan, the differential equations for the response functions can be solved analytically.*

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[1] *C. Y. Chen & S. M. Mahajan , IFSR # 179 (April 1985)*

Positron Production by Fusion Devices and Potential Applications.*

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UCLA

A fusion reactor burning D-^{3}He is a profuse producer of 14.5 MeV protons. Such protons are efficient producers of positron emitters through p-n reactions (typical cross sections ~200 mb). Even existing devices (TFTR, JET) can produce significant numbers of positron emitters (~10^{-3} of the number of protons) if suitable nuclei (e.g., ^{15}N) are added to the plasma. The positron emitters can be used to diagnose the fusion plasma. Some examples are: (1) the number produced measures the energetic proton density, (2) the interaction of the positron emitters with the wall can be used as tracers for impurity wall interactions, and (3) the escape of positron emitters can give a measure of diffusion. Perhaps of greater interest is to use the positrons as tagged electrons to diagnose electron behavior such as confinement time and places of escape. An interesting possibility is that of making a PET image of the plasma; the most critical problem to overcome is the radiation environment. Finally, fusion reactors (including DT reactors through n-2n reactions) could be used as a positron factory (production of proton rich nuclei) which could find many applications in science, medicine, and industry.

* Work supported by USDOE.

PONDEROMOTIVE STABILIZATION OF MIRRORS

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The general ponderomotive force theory derived from oscillation-center equations will be used to address two topics:

1. Nonlinear theory of ponderomotive equilibria.

In the dissipationless model, the system (plasma, magnetic field, RF field) is an infinite-dimensional Hamiltonian system, described by a Hamiltonian and noncanonical Poisson bracket. A nonlinear Lyapunov functional can be constructed from the constants of motions. It yields simple linear and nonlinear stability criteria, expressed in terms of the eigenvalues of the RF wave operator. The analysis exhibits clearly the role of self-consistency, in an additional term in the criteria.

2. Estimates for the RF stabilization of mirrors.

A variational procedure gives the energy threshold for stabilization in arbitrary geometry. It is found that the amount of RF energy needed is, for an axisymmetric mirror, a small but substantial fraction (typically kL_p, where k is the average curvature and L_p is the pressure gradient length) of total plasma thermal energy. To maintain the losses to an acceptable level, this would require the use of antenna with very high quality factor (around 10^5 for a fusion reactor):

$$Q \simeq \frac{ka^2}{L_p} \cdot \frac{\omega\tau}{2\pi}$$

with ω the RF frequency, a the plasma radius, and τ an acceptable energy replacement time.

*Work supported by the Department of Energy.

DOE/ER/53223-6

HYBRID SIMULATION OF QUADRUPOLE STABILIZATION ON THE FRX-C/T FIELD-REVERSED CONFIGURATION EXPERIMENT*

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ABSTRACT

Quadrupole fields have been observed to stabilize the n = 2 rotational instability in the FRX-C/T experiment.[1] We have used a 2 1/2 dimensional quasineutral hybrid simulation code[2] to examine the effect of straight quadrupole fields on truncated rigid rotor equilibria with parameters chosen to approximate those in FRX-C/T. The code is nonlinear and treats ions as particles so that both ion kinetic effects and the modification of the equilibrium due to the quadrupole field are included. For these FRX-C/T-like equilibria we find that the growth rate of the n = 2 rotational instability is virtually unaffected by the quadrupole field until a threshold field strength is reached. For field strengths above this threshold the instability is completely suppressed. The threshold for stabilization by the multipole field in the simulations is approximately a factor of two higher than that observed experimentally. Nevertheless, the qualitative behavior is very similar, as both the simulations and the experiments indicate stabilization of the rotational stability at quadrupole field strengths well below the magnitude of the main axial field. Quantitative differences are most likely due to differences between the equilibria (e.g., the FRX-C/T equilibrium is probably not a rigid rotor). Comparisons with experimental data will be presented.

1. D.J. Rej, W.T. Armstrong, R.E. Chrien, P.L. Klinger, R.K. Linford, K.F. McKenna, E.G. Sherwood, R.E. Siemon, M. Tuszewski and R.D. Milroy, Phys. Fluids 29 (1986).

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*This work was partially supported by U.S. Department of Energy Grant No. DE-FG02-86ER53223.

Computational Studies of Accelerated Compact Toroids*

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An array of computational tools have been developed to study acceleration of compact torus plasma rings and associated applications. 2-D MHD simulations with the HAM code have been used to model formation, compression, and acceleration of compact toroids in the coaxial gun configuration of the RACE (Ring Accelerator Experiment). A 0-D code representing a point model of plasma rings has been developed to solve the momentum, energy balance, and ionization state rate equations including impurity radiation from various species, wall drag, and accelerative heating effects. The most recent developments include a ballooning code that evaluates stability against curvature and Rayleigh-Taylor effects for accelerated rings, and a 2-D electrodynamic code used to model compression of RF cavity fields due to a moving compact torus.

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* Work performed for U.S.D.O.E. by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

A NEW MODE OF ELECTRON SURFACE WAVE ON A VACUUM-PLASMA INTERFACE*

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A new form of surface waves is found on a vacuum-plasma interface which is the surface analog of the well-known Bernstein waves. Using 2-D electrostatic particle-code, the propagation of waves in a plasma-slab has been investigated through simulation techniques. An external magnetic field is imposed parallel to the vacuum-plasma interface and perpendicular to the wave-vector. The existence of these waves in the frequency range between the first two cyclotron harmonics is probably a kinetic effect since it is not predicted by fluid theory. The wave number corresponding to these waves is found to be complex and thus the eigenfunctions have both an evanescent and an oscillating part. Unlike Bernstein waves, these waves are damped. This was observed for a rigid particle reflecting boundary as well as for the case of a free boundary with fixed ions and external magnetic field. Moreover, splitting of spectral lines is observed in both cases. Further, a continuous spectrum has been observed in the case of a free boundary.

* work supported by USDOE and NSF.

RESISTIVE EVOLUTION OF HELICAL MAGNETIC ISLANDS.* G. Miller, A. White, V. Faber, Los Alamos National Laboratory.--In the parameter regime relevant for magnetic fusion, the mass times acceleration term in the plasma equation of motion is exceedingly small and it is reasonable to neglect inertia entirely. In the fluid model, the equation of motion then becomes the equilibrium equation

$$j \times B - \nabla p = 0 \; .$$

Equilibria evolve in time, in the simplest approximation, though a resistive term in Ohm's Law,

$$E + v \times B = \eta j \; .$$

These two equations together with Maxwell's equation constitute the resistive evolution model. This model has a single resistive time scale and therefore avoids the numerical problems associated with having a separate much shorter inertial time scale.

We use the resistive evolution model with prescribed pressure profile to study the growth and saturation of helical magnetic islands in a reversed field pinch, and, for purposes of checks, the Tokamak. The neglect of inertia is justified for ZT-40 conditions when the island width exceeds .001% of the minor radius. In the reversed field pinch toroidal curvature is thought to be unimportant, justifying the assumed helical symmetry, which neglects toroidal effects. Also current rather than pressure effects are dominant, justifying the prescribed pressure approach, which avoids evolving the pressure profile. Furthermore, ergodic field regions, as certainly occur near island x points, may be included by prescribing these regions.[1] In contrast to present three dimensional simulations, equilibrium evolution of single modes, although more limited in scope, is well defined by the equations of a physical model and is numerically convergent.

The development of an equilibrium solver proved to be a challenging problem. Work to be reported consists of equilibrium calculations with the partial flux constraint of specified helical flux in the three flux regions: magnetic axis, island, and wall. This equilibrium method allows the main questions concerning growth and saturation of islands to be simply answered. Relevant internal flux surface quantities that provide the detailed constraint on the equilibrium are computed in preparation for their one-dimensional evolution. Equilibrium results will be presented for the $m=2$ mode in the Tokamak and the $m=0$, 1 and 2 modes in the reversed field pinch. These results will include: numerical convergence studies; correlations of the two dimensional nonlinear solution with the one dimensional linear solution with point discontinuity;[2] and studies to define the critical parameters that have a strong effect on the equilibrium.

1. G. Miller, Phys. Fluids 28, 1354 (1985).
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*Work performed under the auspices of US/DOE.

THE HIGH-FREQUENCY CONDUCTIVITY IN A PLASMA WITH PARALLEL MAGNETIC FIELD GRADIENTS*

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In this work we have formulated the high-frequency conductivity of a plasma immersed in a magnetic field which contains gradients along the field direction for the purpose of improving the wave absorption model relevant to ICRF heating in tokamaks and other magnetic confinement devices. The theoretical model is based on an extension of the standard Vlasov-Maxwell theory for the RF conductivity in a uniform plasma as a superposition of waves with a well-defined ω and $\underline{k}$. However, the nonuniform character of the particle motion along $\underline{B}$ leads to a localized resonance interaction and can effect the degree to which the plasma screening effect on the wave polarization may occur at resonance. In addition to passing resonant particles, trapped particles, especially those whose turning points occur near resonance make a significant contribution to the RF current.

The essential element of the analysis is the replacement of the resonant denominator in the formulation of the conductivity with an appropriate phase integral which includes the nonuniform particle motion along the magnetic field. The uniformly valid evaluation of this integral can be shown to be expressible in terms of Airy functions which remove the singularity inherent in the resonant particle response. Moreover, it is shown that the inclusion of collisions in the particle orbits leads to the standard uniform field result as the collisions become strong enough to decorrelate all but the last few gyro-orbits in the particle motion.

The resulting conductivity operator is formally an integral operator involving both $k_\perp$ and $k_\parallel$ convolutions, but may be expanded in the limit of weak gradients to yield the standard finite Larmor radius expansion modified by a new form of the plasma dispersion function. The results are applied to a reanalysis of the wave absorption properties expected of ICRF heating experiments in tokamaks.

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

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Orbit Integral Propagators*

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Phase coherence during resonant wave-particle interaction deteriorates in the presence of other interacting particles and waves. The net effects can be easily modeled by appropriately generalizing the form of the eikonal representing the interaction.

A propagator technique is then used for evaluating the associated orbit integrals appearing in the quasilinear theory of resonant diffusion. By "differentiating under the integral sign," orbit integral propagators are derived which develop the collisional theory as the solution of a system of ordinary differential equations the initial conditions for which are the results of the collisionless theory.

*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.

VERTICAL STABILITY OF SHAPED TOKAMAKS*

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Elongated cross sections are presently favored in tokamak design because they allow an increased plasma current which improves both its MHD stability and confinement properties. However elongated plasmas are susceptible to axisymmetric vertical instabilites. Sharp tipped triangular or indented shapes[1] have been shown to optimize the beta limits against pressure driven modes and suggest stable operation of tokamaks in the β = 10% to 20% range. We study the vertical stability of these configurations using analytical as well as numerical techniques. The critical distance of a conducting wall needed to achieve ideal MHD stability is evaluated as a function of the plasma elongation and its triangularity parameter[1] δ^* for different current density distributions.

[1]K. Yamazaki, T. Amano, H. Naitou, Y. Hamada and M. Azumi, Nucl. Fusion 25, 1543 (1985)

*Work supported by the U.S. Department of Energy Contract No. DE-AC02-78ET51013

1986 SHERWOOD THEORY CONFERENCE
April 14-16, 1986; New York, New York

A MODEL FOR MINORITY ABSORPTION IN ION CYCLOTRON HEATING*

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We consider minority heating in an inhomogeneous plasma consisting of a deuterium majority and a hydrogen minority. With thermal effects included, the absorption at the minority cyclotron resonance can be understood on the basis of non-resonant coupling of the incoming fast wave to an absorption layer at the minority resonance. To calculate the absorption we generalize the coupling theory of Cairns and Lashmore-Davies [1] for the case of non-resonant coupling such that the perturbed current density in the plasma due to temperature effects is driven by the dielectric-shielded electric field. The result of the dielectric shielding is a small shift in the location of the absorptive layer from the position of the minority cyclotron resonance layer. The polarization of the electric field at this shifted location is then such that ion cyclotron heating occurs for the minority species. Transmission coefficients are calculated for the isolated minority cyclotron resonance, as well as for the total ion-ion hybrid mode-conversion region.

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* This work was supported in part by DOE Contract No. DE-AC02-78ET-51013, in part by NSF Grant ECS 82-13430, and in part by Hydro-Québec Project No. 01844-571-59535.

EQUILIBRIUM OF AXISYMETRIC PLASMAS WITH FLOW

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The equilibrium of plasmas with flow is studied using the axisymmetric steady-state ideal MHD equations. These equations reduce to a p.d.e. for the poloidal flux function and an algebraic equation for the density with four prescribable flux functions. With poloidal flow, the p.d.e may no longer be elliptic and the flow terms enter in a complicated way to the structure of the equation. In particular, the pressure gradient becomes singular at the second transition line/1,2/. In order to resolve the singular behavior, an adaptive flux coordinate code has been written allowing for node concentration in these regions. Accurate solutions with various physcially motivated flux function choices are presented.

* Work supported by US DOE contract DE-FG02-86ER53222

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MODE COUPLING BETWEEN THE FAST AND SLOW BRANCHES OF THE EXTRAORDINARY MODE AT THE FUNDAMENTAL ION CYCLOTRON RESONANCE

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ABSTRACT

The propagation characteristics of extraordinary waves incident toward the fundamental ion cyclotron resonance layer is investigated by a boundary layer analysis.[1] The plasma is assumed to be perpendicularly stratified with respect to the equilibrium magnetic field. We use the relativistic linearized Vlasov equation coupled to Maxwell equations. Outside the layer the geometrical optics assumptions hold. We assume that the ratio of ion thermal speed to the speed of light is small, and the ratio of ion plasma frequency to wave frequency is large. In many plasmas of practical interest the product of these two ratios, ε, is small. We use ε as our boundary layer parameter. By solving the rescaled reordered Vlasov equation, we evaluate the current density, and determine the field equations valid within the layer. In contrast to the higher harmonic ion resonance case,[2] the stretching of the boundary layer variable is determined by Maxwell equations, instead of by Vlasov equation. We find that the inner boundary layer variable must be stretched by ε^4. This leads to a fourth order field equation, indicating the presence of a mode coupling. We identify these modes as being the fast and slow branches of the extraordinary mode by studying the uniform field dispersion relation near the resonance. In the special case of the nonrelativistic limit with purely perpendicular propagation, (which also corresponds to the asymptotic limit of the general case) we derive analytical results. For the basic scattering problems, we obtain transmission, reflection and mode conversion coefficients for the fast and slow mode incidences. For the general case, we prove the reciprocity theorems which state that (i) the transmission coefficient for the fast mode is independent of the direction of incidence, and (ii) the reflected and transmitted mode coupling is the same for the slow and fast mode incidences. When the parallel refractive index is not zero, we use numerical analysis. We find that when the fast mode is incident from the high field side there is no reflected fast mode. The geometrical optics limit is established outside a narrow cone of incidence.

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This work was supported by D.O.E. Grant No. DE-FG02-86ER53233, and by **U.S. Department of Energy** Grant No. DE-FG02-86ER53223.

GLOBAL WAVES IN HOT AND COLD PLASMAS*

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The equations for wave propagation near the ion cyclotron frequency are solved numerically as a two point boundary value problem. Two-dimensional solutions are obtained in the cold plasma limit for helically symmetric stellarator geometry. Superposition of helical modes yields three-dimensional results. In the cold plasma approximation, estimates of power absorption rely on an ad hoc collision model. Results show that power absorption occurs in narrow bands along flux surfaces where they intersect resonant layers.[1] The exact width of these bands depends on the ad hoc collision model assumed. To eliminate the ad hoc collisions requires a solution of the warm plasma equations. Unfortunately, the present generation of computers does not provide sufficient resolution to resolve in two dimensions the very small wave lengths associated with the Bernstein wave. We therefore resort to one-dimensional solutions to obtain insight regarding various approximations which might be extendable to two dimensions. We expand the Vlasov equation to second order in gyroradius and solve the resulting wave equation by finite differencing in a perpendicularly stratified one-dimensional plasma. The electric field parallel to $\vec{B}$ is retained to include collisionless damping of the Bernstein wave. Because the equations are solved implicitly as a two point boundary value problem, the evanescent short wave length Bernstein modes do not grow exponentially as in shooting methods. Results for the full set of warm plasma equations are compared to the approximate method of Colestock and Kashuba[2] and also to various ad hoc collision models.

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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.

NEOCLASSICAL MHD EQUATIONS, INSTABILITIES AND TRANSPORT IN TOKAMAKS*

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Neoclassical MHD Equations. The moment approach[1] to neoclassical-type processes is used to derive the flows, currents and resistive MHD-like equations for studying equilibria and instabilities in axisymmetric tokamak plasmas operating in the banana-plateau ($\nu_* \sim 1$) collisionality regime. The resultant "neoclassical MHD" equations[2] differ from the usual reduced equations of resistive MHD primarily by the addition of the very important viscous relaxation effects within a magnetic flux surface. The primary effects of the parallel (poloidal) viscous relaxation are: (1) Rapid ($\sim \nu_{ii}$) damping of the poloidal ion flow so the residual flow is only toroidal; (2) addition of the bootstrap current contribution to Ohm's law; and (3) an enhanced (by B^2/B_θ^2) polarization drift type term due to parallel flow inertia, which causes the equations to depend only on the polodal magnetic field B_θ. Gyroviscosity (or diamagnetic viscosity) effects are included to properly treat the diamagnetic flow effects. The nonlinear form of the neoclassical MHD equations is derived and shown to satisfy an energy conservation equation.

Neoclassical MHD Instabilities. The type of instabilities obtained from the neoclassical MHD equations are analogous to those in resistive MHD[3]: resistive-g, tearing and rippling. The pressure-gradient-driven neoclassical MHD modes[4] depend on the parallel viscosity μ_e (which allows the expansion free energy to be tapped) instead of on magnetic field curvature. Neoclassical MHD tearing modes[5] gain access to the expansion free energy in their linear regime through the bootstrap current, but ultimately evolve[5,6] into the usual resistive MHD Rutherford regime for nonlinear tearing modes. Rippling type modes are also possible for $\nu_{*e} \sim 1$ through density perturbations. Neoclassical MHD instability growth rates are comparable[4,5] to their resistive MHD counterparts, but their resistive layer widths are increased by $(B/B_\theta)^{2/3} \gg 1$.

Neoclassical MHD Instability-Induced Transport. Turbulent transport is estimated for the pressure-gradient-driven modes using the Carreras-Diamond formalism[7] and found to be $\chi_e \sim (\eta/\mu_0)(\mu_e B_\theta/\nu_e)^2 (m_i/m_e)^{1/2}$, $D/\chi_e \sim (m_e/m_i)^{1/2}/(\mu_e B_\theta/\nu_e) \ll 1$, where $\mu_e/\nu_e = 2.3\sqrt{\varepsilon}/(1 + 1.02\,\nu_{*e}^{1/2} + 1.07\,\nu_{*e})$. For an ohmic heating power balance this leads for $\nu_* \gtrsim 1$ to $\beta_\theta \sim (m_e/m_i)^{1/6}(\mu_e/\nu_e)^{-2/3} \lesssim 0.3$ and $\tau_E \sim n_e^{13/14} a^{4/7} R_0^{15/7} q^{5/7} B_\theta^{1/7}$. For auxiliary heating (small ν_{*e}) $\tau_E \sim P_{aux}^{-5/7} n_e^{3/7} a^{1/7} R_0^{12/7} I^{8/7}$. These τ_E scaling laws are reasonably close to experimental results.

*Work supported by U.S. DOE Grant # DE-FG02-86ER53218.
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SAWTOOTH CRASH TIME

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Although the crash in the temperature during a sawtooth is commonly associated with the growth of a resistive mode, the experimental crash time is often much shorter than the time scale given by resistive reconnection.[1] It is shown that an initial current profile with skin currents such that q falls below one at a finite radius r_s and is flat and near unity around the magnetic axis can cause a sawtooth crash with short MHD time scale. For such a q profile the reversed helical flux is localized around r_s. Such skin currents can form in discharges with good central confinement.[2] The m=1 mode grows on a hybrid resistive time scale, reconnecting the reversed flux around r_s. The reconnection of the reversed flux is completed when the island is of the order of the width of the skin current, ending the resistive phase of the instability. The island then rapidly expands across the center of the discharge as the energy in the bent field lines is released. The large increase in the mass flow at this stage depends only on $\Delta q = 1 - q_{min}$, where q_{min} is the minimum value of q for the initial profile, and not on the resistivity. The crash time t_c is approximately by $t_c \sim \tau_A/\Delta q$, where τ_A is the toroidal Alfvén time. The rapid crash in the temperature results from convection by this large flow. Two-dimensional MHD simulations of this fast crash are presented.

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

COLLISIONLESS ELECTRON TEMPERATURE GRADIENT INSTABILITY

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We have studied the stability of electron temperature gradient driven modes in a collisionless plasma with magnetic shear. Two coupled integral equations for the electrostatic and parallel vector potential have been solved numerically. The modes are unstable in the short wavelength region between the electron and ion gyroradii. Using mode properties derived on the basis of our numerical studies we estimate the anomalous electron energy transport induced by these modes.

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

ECH Stochastic Heating in Stellarators

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ABSTRACT

The Electron Cyclotron Resonance stochastic interaction in a homogeneous, unpolarized radiation field is investigated. The ECH heating rate on a flux surface, in an actual stellarator field, is calculated by averaging the uncorrelated energy jumps associated with each individual resonance crossing.

$$\left\langle \frac{dw_\perp}{dt}(\psi) \right\rangle = \pi \left(\frac{eE}{B_o}\right)^2 \sum_j \frac{B_o}{L} \frac{1}{\left| \underset{\sim}{b} \cdot \nabla B \right|_{\cdot j}}$$

The RF absorbed power is obtained by integrating the flux surface-averaged interaction rate across the plasma volume. The plasma density is assumed constant on a flux surface. Predictions of this model for the Proto-Cleo Stellarator and Torsatron are compared.

In the Proto-Cleo Torsatron the effects of the large helical magnetic ripples are the dominant factor. The effects of modification of the magnetic topology (e.g., reduced O configurations) on the ECH heating efficiency are also investigated. Enhanced absorption efficiency results from improved confinement characteristics and enhanced ECH heating rates.

This work is supported by the U.S. Department of Energy Grant No. DE-FG02-86ER53216.A000 and Oak Ridge National Laboratory Contract No. 19X-27434C.

Numerical Simulation of Ion Cyclotron Wave Propagation in Mirror Confined Plasmas

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In plasmas, such as those found in the central cell of tandem mirrors, the ion cyclotron wave could effectively heat the bulk ions if it could be efficiently propagated into the plasma. However, in present mirror experiments various geometrical and physical constraints generally inhibit the propagation of the ion cyclotron wave. In this paper the ion cyclotron wave propagation in axisymmetric mirror geometry is simulated using the code GARFIELD. This code is designed to calculate the three-dimensional structure of ICRF fields in axisymmetric mirror equilibria. The code includes both radial and axial magnetic field and density gradients in the calculation and uses advanced numerical methods that can accommodate the very large mesh size required for resolving the slow wave. Conditions that most effectively optimize power flow into the ion cyclotron branch of the RF wave spectrum in a 2-D mirror geometry are discussed. All three components of the total wave electric and magnetic field produced by these waves are solved. Because of the two dimensional nature of the equilibrium, problems can arise in identifying which particular branch the wave fields belong since the equations can no longer be cleanly separated. These and other problems are discussed.

RESONANT TRANSPORT IN A RIPPLED TOKAMAK

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Particle transport in a slightly rippled tokamak is studied using a 2-D mapping representation[1]; collisionality is modeled by a bounce-averaged Monte Carlo operator. Attention is focused on the case of precession resonance, where the usual adiabatic dependence of the precession rate[2] on the bounce angle fails. Collisionality then enters into the map in two ways, one of which is analogous to a mirror transport process studied by Chirikov[3]. The other limiting case was studied, in no specific physical context, by Rechester, Rosenbluth and White[4]. Together they give a rich variety of subregimes for resonant transport.

*Work supported by DOE Contract #DE-AC02-76-CHO-3073.

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ELECTROMAGNETIC TOROIDAL QUASILINEAR TRANSPORT COEFFICIENTS FOR TRAPPED-ELECTRON AND KINETIC MHD-BALLOONING MODES*

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In previous studies[1], comprehensive electromagnetic kinetic calculations of linear eigenfrequencies and eigenfunctions have been carried out for a number of tokamak plasmas under realistic operating conditions. We now also calculate the corresponding electromagnetic (or electrostatic) quasilinear transport coefficients for particles and energy for each species, employing the formulation of Horton[2]. Ambient gradient or mixing length type estimates for saturated amplitudes are used here. Results for the trapped-electron mode and the kinetic MHD-ballooning mode will be presented for cases corresponding to the interior region of the ISX-B tokamak and to the interior and edge regions of the PDX tokamak for an H-mode discharge.

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

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Numerical Calculation of Mercier Stability Limits in Spheromaks.

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In the past, Spheromak equilibrium and stability have been calculated in the ideal MHD, zero pressure gradient limit. Since this compact toroidal device has recently been receiving greater attention, finite pressure gradient effects become increasingly important. By iteratively solving the Grad-Shafranov equation and Mercier Criterion stable field structures, pressure profiles, and beta limits can be determined. Marginal Mercier stability is found for given pressure profiles and optimal stability is found making no assumption on pressure profile. For the latter, $\langle\beta\rangle_{vol}$ as high as 1.5% has been calculated for operating conditions corresponding to sustained Spheromaks. Calculations have also been made for Spheromaks with current holes leading to $\langle\beta\rangle_{vol} = 5.8\%$.

Alfvén Waves in a Shear Magnetic Field*

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The Alfvén waves in sheared magnetic fields were studied mainly from the standpoint of the plasma stabilities.[1] Now that the Alfvén waves themselves become important for high β, toroidal plasmas, the systematic studies of the rf Alfvén waves propagation and absorption are needed. This paper describes the attempt to understand the wave from both wave[2] and MHD approaches.

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

Ion Bootstrap Current and the *H*-mode

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The *L*- to *H*-mode transition in ASDEX has been found to be strongly influenced by the ion grad-B drift direction.[1] It was shown theoretically[2] that the ion temperature gradient near the plasma edge is significantly affected by the grad-B drift direction. An attempt is made here to understand the link between the ion physics and the electron transport, in terms of the current density profile. The ion bootstrap current driven by large gradients can significantly alter the current density profile near the edge. It contributes a pedestal and decouples the current density profile from the electron temperature profile. It is speculated that this may be responsible for the better electron energy confinement in the *H*-mode, for the following reason. It is believed that tearing mode stability implies current density and temperature profiles which have well-defined shapes, and that the global confinement scaling is determined by drift wave turbulence with the profile constraints imposed by tearing mode stability. Adding a pedestal to the current density profile is known to improve tearing mode stability, and may therefore improve the global energy confinement by changing these constraints. The current density profiles expected under *H*-mode conditions will be presented.

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

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Ion Viscosity Stabilization of Resistive Internal Kinks

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The linear stability analysis of resistive $m^0=1$ modes is presented, including the effects of ion viscosity ($\mu_\perp \propto \nu_{ii}$), ion diamagnetic frequency ($\omega_{di} \propto \rho_i$) and electron drift frequency ($\omega_{*e} \propto T_e dn/dr$). We find that, at high temperatures, moderate values of the ion viscosity parameter $\hat{D}$ stabilize resistive internal kink modes, when β has values appropriate for near ideal marginal stability ($\delta W_{min} \simeq 0$). High temperature regimes are defined as:

$$\omega_{di}/\omega_A \sim \beta_i^{1/2} (\rho_i L_s)/(r_n r_0) > \varepsilon_\eta^{1/3}$$

where $\omega_A = V_A/L_s$ is the Alfven frequency, L_s is the shear length, r_n the density gradient scale length, $\varepsilon_\eta = \nu_\eta/\omega_A \propto \eta_{||}$ the inverse magnetic Reynolds number and all quantities are defined at the $r=r_0$ mode rational surface where $q(r)=1$. Note that $\omega_{di}/(\omega_A \varepsilon_\eta^{1/3}) \sim T^{3/2}$. The relevant ion viscosity parameter is:

$$\hat{D} = \nu_\mu/\nu_\eta \simeq (3/10)\beta_e (m_i T_e/m_e T_i)^{1/2} \sim \mu_\perp/\eta_{||}$$

where $\nu_\mu \propto \mu_\perp$ is the rate of collisional transport of ion transverse momentum. In a deuterium plasma with $T_e=T_i$ and $\beta=1\%$, $\hat{D}=0.18$. Stabilization is found for $\hat{D} > \hat{D}_c \sim \varepsilon_\eta (\omega_A/\omega_{di})^3$. The stabilization can be understood as follows: in high temperature regimes, finite Larmor radius ($\propto \omega_{di}$) significantly reduces the growth rate of the resistive internal kink. A residual growth ($\gamma \propto \eta_{||}$) or damping ($-\gamma \propto \mu_\perp$) occurs when either the resistivity or the viscosity dominates. The value $\hat{D}_c$ is obtained by requiring that the two competing effects cancel each other. This theory is relevant to present and near future Tokamaks for which $\nu_{ii} > \omega$. It may also explain the nonsawtoothing Tokamak discharges that have been recently observed.

1986 SHERWOOD THEORY CONFERENCE
April 14-16, 1986; New York, New York

RUNAWAY ELECTRON DISTRIBUTIONS AND THEIR STABILITY WITH RESPECT TO THE ANOMALOUS DOPPLER RESONANCE*

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The stability of runaway electron distributions with respect to the anomalous Doppler resonance is examined. Distribution functions are first calculated numerically within a region up to 35 thermal velocities using a finite-element Fokker-Planck code. We find a two-temperature distribution composed of a (shifted) thermal bulk and a hot component which is broadened and Maxwellian in the perpendicular direction. On this basis and using the test-electron equations we analytically construct the runaway distribution function. Stability thresholds in $(\omega, k_{||})$-space are then determined for $\omega_{pe}/\Omega_{ce} \leq 2$ and for electric fields $E/E_c \leq 0.1$. In particular, we find that, in this range of parameters of interest to tokamaks, instability is absent unless the runaway tail extends beyond 30 thermal velocities.

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* This work was supported in part by Hydro-Québec Project No. 01844-571-59535 and in part by DOE Contract No. DE-AC02-78ET-51013.

The Calculation of Lyapunov Spectra*

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Some of the useful information of complicated dynamical systems may be obtained by linearization around their chaotic orbits. In particular, the magnitude and directions of the ellipse that evolves from an initial small sphere of realizations in the phase space can be deduced from a time displacement matrix which relates the initial bundle of realizations to its later configuration.

The singular values, and the associated orthogonal matrices of the time displacement matrix are utilized in studying these properties. One of the important properties is that asymptotically, principal stretching, and contraction directions depend only on the location in phase space, and not on the orbits.

These dynamical properties of the Lorenz model are studied as an example and a comparison with others' work.[1]

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

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PLASMA PRESHEATH IN A COLLISIONAL PLASMA*

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An equation for the variation of the electrostatic potential in the sheath and presheath regions of a collisional plasma with arbitrary ion temperature is derived. The plasma is assumed to be one-dimensional with perfectly absorbing walls and a Boltzmann distribution of electrons. Ion-ion Coulomb collisions are included in the analysis. The collisions are described by the Bhatnagar, Gross, and Krook [1] collision term, which conserves particles and momentum. The mean-free-path for Coulomb collisions is assumed independent of both velocity and position.

The equation is solved numerically in the presheath region for low to moderate collisionalities. In the collisionless limit, the solution reduces to previous analytical results [2]. At moderate collisionality, the potential at the plasma side of the sheath is increased, while the potential at the wall remains constant. In addition to the potential variation and the wall potential, the ion distribution function is also calculated.

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Electron Cyclotron Heating in ATF*

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Results are presented using the RAYS[1] geometrical optics code to calculate electron cyclotron wave propagation and heating in the ATF device under construction at Oak Ridge National Laboratory. The intent of this work is to make predictions about the outcome of various heating scenarios as well as to give guidance in designing a heating system. We investigate first and second harmonic cyclotron heating with the parameters predicted for steady state ATF operation. The calculations are done to predict the sensitivity to change in coil currents, plasma density, and antenna parameters. From these results we identify compromises which represent the optimum heating strategies as well as develop an intuitive picture of electron cyclotron heating in torsatron devices. Our basic conclusions are that second harmonic heating with the extraordinary mode gives the best result, with fundamental ordinary mode heating being somewhat less efficient. Assuming the antenna location is restricted to the low magnetic field side, it should be placed at the toroidal angle where the helical coils are at the sides $\phi = 0°$ for fundamental heating, and at $\phi = 15°$ (helical coils at top and bottom) for second harmonic heating. These recommendations come directly from the ray tracing results as well as a theoretical identification of the relevant factors affecting the heating.

* 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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Stability of Cylindrical Plasma in Bessel Function Model with Vacuum Region*

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The complete eigenfunction of the Euler equation for the helical displacement ξ in the case of force free plasma with a constant μ (eigenvalue) has been given by a class of Bessel functions. The expansion coefficients for the eigenfunctions are determined from the boundary condition: continuities of the helical flux and magnetic pressure and discontinuity of μ at the helically deformed plasma-vacuum interface. The instabilities of free boundary current driven ideal (kink) and tearing modes are studied by examining, respectively, the zero of helical flux and the discontinuity of radial derivative of helical flux (Δ') at the singular surface. In this model the helical perturbation and thereby the stability is described by k/μ, μa, and d, where k is the wavenumber in the axial direction, a is the plasma radius, and d is the vacuum field thickness. The marginally stable boundaries in the space (k/μ, μa) for the ideal and tearing modes are calculated by numerically solving the transcendental equations $\xi = 0$ and $\Delta' = 0$, respectively, for various values of the vacuum thickness.

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

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Ion Trapping Rate for Thermal Barriers*

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The thermal barrier employs a potential dip to isolate the center cell electrons from the plug electrons. Collisions cause the ions passing over the inboard magnetic field peak to become trapped in this electrostatic well. To maintain this potential barrier these ions are removed or pumped by charge exchange or some other mechanism. The rate at which they are pumped must equal the collisional trapping rate in order to maintain the barrier. A variational formulation is employed to recover the analytic expression of Carrera and Callen[1] for the ion trapping rate which they obtained by solving a boundary value problem in velocity space. The trial function employed is a modified form of the one introduced by Cohen[2] in a study of axial potential profiles in thermal barriers. The variational procedure used is similar to that developed by Li and Emmert[3] to obtain a semi-analytic evaluation of the ion trapping rate. The variational treatment is a useful alternative to the Fokker-Planck code results of LoDestro and Futch.[4] With improved trial functions and/or more refined collision operators, better agreement with their numerical results would be possible, but at the expense of analytic simplicity.

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Ideal MHD Stability Properties for Highly Elongated Spherical Shell and Racetrack Tokamaks*

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Ideal MHD equilibrium and stability properties for highly elongated spherical shell and racetrack tokamaks have been determined. Highly elongated tokamaks can achieve ohmic ignition at moderate toroidal field and moderate size. When the safety factor is held fixed, the minimum toroidal field required to achieve ohmic ignition is inversely proportional to elongation and the current density is proportional to elongation so the required high toroidal current can be achieved at small radius. The spherical shell tokamaks have robust equilibrium solutions and the equilibria are stable to ballooning and Mercier modes at high β's with no programming of the field-shaping coils. The elongated racetrack tokamaks do not have robust solutions and are not stable to ballooning and Mercier modes with no programming of the field-shaping coils. In order to accurately determine with GATO the stability properties of these elongated tokamaks, it has been necessary to make significant changes to the equilibrium[1] and stability[2] computer programs. It has also been necessary to go to a much finer grid for both computations. The spherical shell tokamaks have very favorable stability properties to the n=0 kink mode. A detailed analysis is presented to include the necessary position of a stabilizing wall for both these tokamaks for n=0, n=1, and n=2 modes.

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Manifestly Gauge-Invariant Relativistic Ponderomotive Theory*

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We have found that eikonal wave perturbations to the Lagrangian action for a relativistic charged particle in the guiding-center representation can be written in *manifestly* gauge-invariant form. To do this, it is necessary to abandon the usual approach of expanding the eikonal wave perturbation in a series of Bessel functions of $k_\perp \rho$. Instead, we first perform a Lagrangian gauge transformation, and then we expand in a series of functions that are related to indefinite integrals of Bessel functions. This allows us to develop an oscillation-center theory to arbitrarily high order in the wave amplitude expansion parameter and be guaranteed of *manifest* gauge invariance at every step of the way. This is a significant improvement over past attempts at ponderomotive theory for which gauge invariance of the results was either not established, or established only by laborious calculation after the fact. At present, we have worked out the oscillation-center perturbation series as far as the ponderomotive Hamiltonian, and we have applied the K-χ theorem to get the linear susceptibility. This work is useful for studying the RF heating of magnetically confined plasmas, induced scattering, FEL theory, etc.

* Work performed for U.S.D.O.E. by Lawrence Livermore National Laboratory under contract W-7405-ENG-48, and by Lawrence Berkeley Laboratory under contract DE-AC03-76SF00098.

VOLT SECOND CONSUMPTION DUE TO SAWTOOTH ACTIVITY*

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Two methods have been employed in analyzing the poloidal magnetic flux balance (volt-second consumption) in tokamak experiments: an "axial method" based on volume integration of Faraday's law,[1] and a "Poynting flux method" based on volume integration of the Poynting flux.[2] The methods differ in their relative assignments of resistive dissipation and internal flux but both yield the correct total volt-seconds if the magnetic flux is diffusive and an appropriate Ohm's law is used to relate the current and toroidal electric field. In the presence of sawtooth activity, however, there is poloidal flux redistribution and conversion of magnetic energy to plasma kinetic energy which is not accounted for in Ohm's law; the rapid change in $\partial B/\partial t$ at the sawtooth crash leads to a voltage spike (Faraday's law) which must be incorporated into both methods for predictive analysis. If the pre- and post-disruptive states are presumed known (e.g., Kadomstev's model) the time integrals of the volt-second balance over the sawtooth crash can be evaluated self-consistently in both the axial and Poynting flux methods. In low-q, elongated plasmas such as the Compact Ignition Tokamak (CIT) the dissipation of magnetic flux and energy by sawtooth activity can exceed the resistive dissipation.

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

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KINETIC FIELD-REVERSED CONFIGURATION EQUILIBRIA

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Two-dimensional FRC equilibria have been obtained to date by using magnetohydrodynamics without flow to model the plasma. Since two of the most important features of FRCs are ion rotation and large ion orbits, it is desirable to compute equilibria using a kinetic model. This is particularly important because of recent advances in the kinetic stability theory for FRCs and because of the possibility of improving stability by injecting energetic ion rings. We have developed a Grad-Shafranov-like equation that describes axisymmmetric FRC equilibria in the limit of zero electron mass and zero electron temperature, i.e., in the limit of the Vlasov fluid model. The ion distribution function is chosen to be a linear combination of a finite temperature Maxwellian and a finite temperature rigid rotor. This choice for the distribution function implies a fixed relation between the electric potential and the ion density, and hence between the electric potential and the pressure. The electric potential can be shown to be a function of the flux function, ψ, and the equilibrium equation has the form of the usual Grad-Shafranov equation with a modified right-hand side. We define two density functions, n_1 for the Maxwellian part of the ion density and n_2 for the rigid rotor part:

$$n_1 = n_o(1-\epsilon)\exp(-e\phi/T_1)$$

$$n_2 = n_o\epsilon\exp\left[(-e\phi + e\Omega\psi + Mr^2\Omega^2/2)/T_2\right]$$

where ϵ is a parameter that governs how much of each kind of profile to include and where Ω is the ion rotation frequency. In the Vlasov fluid theory limit the equilibrium equation has the form

$$\Delta^*\psi = \mu_o r^2\left[(n_1 + n_2)e\phi' - n_2 e\Omega\right]$$

where $\phi = \phi(\psi)$, $\phi' = d\phi/d\psi$, and where e is the charge of a singly charged ion. Dennis Hewett's MHD equilibrium code is being modified to compute such kinetic equilibria; preliminary results will be presented.

Work supported by USDOE

The Issues of Boundary Conditions and Time Discretization when Simulating MHD Dynamics

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This presentation deals with two important subjects involved in the simulation of MHD dynamics in contemporary fusion devices.

The first is the question of consistent boundary conditions when modeling the RFP. Of particular concern is the choice of constant current, which when combined with other commonly used boundary conditions, could lead to an inconsistency. The problem originates from the fact that in the absence of viscosity, the normal component of velocity does not in general want to approach zero at the wall. This can lead to violation of the normal component of Faraday's law because of an incorrect implementation of a zero tangential electric field boundary condition, and can ultimately result in a non-solenoidal magnetic field. Simulations are carried out with the 3-D, nonlinear, compressible code TEMCO. Cases both with and without Hall terms are presented.

The second subject is the progess towards implicitizing TEMCO, in particular for applications in toroidal geometry (such as the spheromak). It is highly desirable to model long-time resistive evolution on its own timescale rather than on the Alfven timescale. Furthermore, inclusion of Hall effects in Ohm's law lowers the maximum allowable timestep for an explicit operator, often to the point of intractability. A highly promising technique of late is the "semi-implicit" method, which involves the use of simplified, artifical terms whose implicit discretization is able to economically achieve numerical stability. For toroidal geometry the problem is more severe because of the inability to economically expand in a poloidal Fourier series. Hence, when invoking an implicit method one must solve a block 9-banded system rather than a block tridiagonal system.

*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.

PAP: AN APPRENTICE PROGRAM FOR DOING PLASMA PHYSICS THEORY*

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Although current capabilities of symbolic computation and artificial intelligence are not adequate to do all the types of thinking a physicist does in solving physics problems, much of what the human theorist does can be effectively imitated by a computer. We present a description of an early stage of implementation of PAP, a Plasma APprentice program, for aiding plasma theorists in developing plasma physics theory, by performing those tasks which the theorist normally must do, but which are now amenable to machine imitation. In addition to a simple algebraic capability given to it by MACSYMA, the apprentice has a "knowledge base" containing its understanding of plasma theory, which can be accessed by the human user for pedagogic purposes, as well as by the apprentice itself in carrying out its functions, and some ability to do the kinds qualitative of heuristic reasoning necessary to the human theorist in solving problems. These facilities, directed by an overall control structure for planning a solution route for a given problem, enable the apprentice itself to do plasma calculations, informing the user of the progress of the calculation, and prompting him when a decision is needed the apprentice is not equipped to handle. Some extensions planned for the future will be discussed.

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

Can Strong ICRH Limit Explain n-mode in RFC-XX-M*

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Recently a new and unexpected equilibrium (n-mode) in the Nagoya RFC-XX-M cusp-stabilized mirror has been discovered[1] in which the axial potential distribution is inverted: strongly negative in the central cell and throat regions and slightly positive in the cusp end cells. Since the system is strongly dominated by ICRF heating, we expect that it is the non-Maxwellian ion species leaning on the magnetic field that largely controls the density-potential relation. We have used model ion distribution functions that possess the envisaged features of the expected distributions for five classes of ions present in the system. These model distribution functions are continuous throughout ε, μ phase space and permit analytic expressions connecting the two significant density ratios, central-cell to end-cell and central-cell to throat, to the two significant potential differences, central-cell to end-cell ion barrier and central-cell to throat electron barrier.

We propose that during n-mode operation a second harmonic heating layer exists in the cusp driving the magnetically trapped cusp ions to high energies, making them susceptible to magnetic moment pitch angle scattering into the loss cone. This effect together with a sufficiently strong cusp end cell particle source leads to high cusp end cell densities *and* comparable ion and electron end cell loss rates. This may explain why the end cell to wall potential difference is small and how in turn the central cell potential is forced to be negative.

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*This is a report of work sponsored by the Department of Energy under Contract No. DE-AC03-83SF11713.

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SHERWOOD THEORY MEETING 1986

Energy Confinement in $\nu_{*i} \ll 1$ Plasmas *

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Recently, experimental results have indicated that significant anomalies in ion thermal transport in tokamaks may be present. Most attempts at a theoretical explanation of this phenomenon have been based on the η_i-mode, a pressure-driven sound wave.

Here, we explore ion thermal conduction and energy confinement in $\nu_{*i} \ll 1$ plasmas, where trapped particle effects are important. Transport due to η_i-driven trapped ion modes,[1] appropriate to the relevant ($\nu_{*i} \ll 1$, $\nu_{*e} < 1$, $\nu_{\text{eff},e} > \bar{\omega}_D$) parameter regimes is estimated. The implications of these results for the proposed C.I.T. is discussed. The effect of trapped-ion driven resistive interchange modes on anomalous electron transport is also discussed.

In addition, a more detailed nonlinear theory of trapped-ion driven turbulence is being developed. Renormalized two-point theory is being applied to develop a deeper understanding of saturated trapped-ion mode turbulence. Results will be presented.

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

NONLINEAR PLASMA RESPONSE TO EXTERNALLY APPLIED FIELDS IN PLASMA SIMULATIONS*

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It is generally difficult to observe subtle processes in a simulation plasma, such as those found in the vicinity of mode conversion layers of an inhomogeneous plasma, due to the enhanced thermal fluctuations. We present a method which is designed to observe these effects when external driving currents outside the plasma boundaries are imposed.

The simplest possible system is chosen to demonstrate the procedure--the plasma response to a test charge. For short times the thermal fluctuations are not greatly affected by the presence of the test particle. Therefore, we perform the simulations twice, once with the test charge and once again without it. Subtracting the potentials from the two runs gives the plasma response. The results give excellent agreement with the theoretical expressions for finite-size particle shielding clouds in an unmagnetized plasma.

We extend this procedure to electromagnetic plasma simulation models where driving currents outside the plasma boundaries are imposed and the plasma responds to a spectrum of modes launched by a particular antenna configuration. Simulation runs with and without the external rf are performed and the resultant fields subtracted. The radiation patterns in the presence of the plasma are compared to the vacuum field patterns. Results are presented for oscillating current sheet and Nagoya Type-III antennas.

* Work supported by USDOE.

ELECTRON CYCLOTRON RESONANT HEATING OF TRAPPED ELECTRONS IN MIRROR FIELD

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ABSTRACT

Trapped electrons always exist in confinement devices with nonuniform magnetic field configurations. The effect of their bounce motion on ECRH is of considerable interest for many reasons. These include the understanding of the formation mechanism of annuli of hot electrons in Elmo Bumpy Torus (EBT) and the possibility of creation of similar hot electron annuli in tokamals plasmas for stability purpose. In our previous work[1], the results show that the bouncing motion of electrons serves to alleviate the detuning effect of frequency mismatch and efficient heating can be achieved. However, a simple harmonic bouncing force introduced by an external force field was used in the previous analysis to model the mirror force. In the present work, ECRH of bouncing electrons in the parabolic magnetic mirror is analyzed. Heating by both ordinary mode and extraordinary mode is examined. The results of heating rate for each case and for the fundamental and second harmonic resonances will be presented. The effect of resonance heating on the excursion amplitude of bouncing motion will also be discussed.

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Axial Eigenmodes of Ion Loss-Cone Instabilities in the TARA Plug and Anchor*

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The plug cell of the TARA tandem mirror, with neutral beams building up a sloshing hot ion component, may be subject to ion loss-cone instabilities (DCLC and ALC) at frequencies comparable to the ion cyclotron frequency and its harmonics. The anchor cell may also be subject to these instabilities, if hot ions are required for MHD stability. Knowledge of the eigenmodes of these instabilities in TARA is needed in order to interpret the results of a microwave scattering diagnostic which will look for fluctuations in this frequency range.[1] As a first step, axial eigenmodes have been calculated (locally on each field line) in the plug and anchor cells, using the MSTARA code. This code uses a vectorized linear differential equation solver, which is about ten times faster than conventional O.D.E. solvers, to solve the axial eigenmode equation. For the anchor, assuming a peak density of $2 \times 10^{12} cm^{-3}$ hot ions (at $9keV$), and a potentially confined warm ion distribution ($300eV$) with density 1.6×10^{12} at the inner mirror throat, we find that lower frequency modes are stabilized by the warm ions, but that unstable modes with frequency $\omega \approx 8\omega_{ci0}$ (where ω_{ci0} is the midplane ion cyclotron frequency) can localize in the outer half of the anchor, avoiding the warm ions. For modes localized on axis (i.e. with no density gradient), the maximum growth rate is $0.45\omega_{ci0}$, at $k_\perp \rho_i = 38$, if there is no end loss stream. End losses from the central cell have a negligible effect on anchor stability, but a collisional end loss current from the transition region ($0.2A/cm^2$, or $36A$ total) reduces the growth rate to $0.15\omega_{ci0}$, and an end loss current 1.8 times greater completely stabilizes the modes localized on axis. For the plug, assuming a hot sloshing ion distribution with peak density $1.2 \times 10^{13} cm^{-3}$ and a thermal barrier with a potentially confined warm ion distribution of peak density $10^{13} cm^{-3}$, we find unstable modes with $\omega \approx 4 - 8\omega_{ci0}$ and $k_\perp \rho_i \approx 13 - 30$, with maximum growth rate $0.5\omega_{ci0}$, localized on axis, if there is no stream. A stream of $0.7A/cm^2$ (only 7% of the collisional end loss rate for the central cell) can stabilize these modes. Assuming a gaussian radial density profile of radius $7.5cm$, and looking at modes localized on a field line $5.5cm$ off axis, we find a strong hot ion density gradient which is destabilizing. Low frequency modes remain stable, but for $\omega > 7\omega_{ci0}$ and $k_\perp \rho_i > 13$, there are modes with high growth rates even with stream current greater than $1.5A/cm^2$. Results will be presented (if available) from a radial ray tracing code, which will give 3-dimensional eigenmodes, and show whether the localized instabilities described above are convectively or absolutely unstable. This code uses a novel ray-tracing method which is valid even when the group velocity has a large imaginary part.

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* Supported by U.S.DOE Contract No. DE-ACO2-78ET-51013

Abstract for
1986 Sherwood Theory Conference
April 14-16, 1986
New York, New York

MODELING POWER DEPOSITION IN ECH EXPERIMENTS*

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A number of electron cyclotron heating experiments have been and are being carried out in various Tokamaks. In order to understand the localized power deposition, associated with ECH, it is helpful to model the power deposition that is likely to occur in an actual experiment. To accomplish this, one often resorts to a simulation that utilizes ray tracing. However, proper modeling of power deposition is strongly dependent on the choice of rays used to represent the actual antenna pattern. Difficulties in the choice of rays to represent the antenna power are discussed. For example, increasing the number of rays should not result in a change in the predicted deposition profile. We use the ray tracing code TORAY to simulate power deposition profiles that occur in mc ECH experiments on T–10, TFR, PLT/PDX and D3. Particular attention will be given to the dependence of power deposition on antenna size, machine size and plasma parameters.

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

DECIMATION IN TURBULENCE

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The modal analysis of turbulent systems will lead to an infinite set of coupled nonlinear ordinary differential equations. For numerical tractability, this infinite set must be truncated to an appropriate finite set of equations. However, the effects of fine-scale motion in the turbulence can not be ignored.

In the decimated amplitude scheme, originally proposed by Kraichnan[1], the effect of the truncated modes on the large-scale turbulence is modelled by including a stochastic forcing term. For the decimated system to have the same statistical behavior as the full system, a set of statistical constraints must be imposed on this forcing term.

This decimated amplitude scheme, as well as the sensitivity to the level of truncation and the non-Markovian memory in the forcing stochastic term, will be applied to various model systems.

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Minimum Energy State of MHD Equilibria*

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Minimizing the total plasma energy by ideal MHD perturbations[1] results in the equilibrium equation with two out of three variables undetermined. Further relaxation[2] with nonideal MHD perturbations subject to the constraint of total plasma current leads to a unique current profile for given central and edge safety factors, manifesting the nature of "profile consistency."[3] This paper further presents the relaxed MHD equilibria resulting from arbitrary variations in the poloidal fluxes constrained by the total current. The equilibrium state governed by $\Delta^*\psi + \Lambda \exp(\psi) = 0$ reveals properties of profile consistency, H–L mode bifurcation, and disruption condition. A unique current profile, relatively insensitive to β_p, predicts a transport coefficient which is peaked at the plasma edge in agreement with experiments. Bifurcated solutions exist for the given total current and the profile parameter Λ, indicating higher edge current density and central q (broader current profile) for H-mode. Loss of equilibrium occurring at $\Lambda > \Lambda_c$, where $\Lambda_c = 2$ in the cylindrical limit, gives a major disruption condition when the current density gradient exceeds a threshold that is related to the ratio of current densities at the center and edge. The toroidal effect and the noncircular cross sections will also be discussed.

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

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THREE DIMENSIONAL ANALYSIS OF ICRF WAVE PROPAGATION AND ANTENNA LOADING CHARACTERISTICS*

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Numerical results are presented from a fully three-dimensional wave propagation and deposition code used to investigate ICRF heating in large tokamaks. Based on a contraction of fourth order mode conversion equations, the study employs the usual dielectric tensor including relevant finite temperature corrections. Energy transferred from the fast wave, either via direct damping or through mode conversion is deposited locally near the mode conversion zone and is preserved in the dielectric function.

The code utilizes Fourier decomposition in both axial and poloidal directions, and in particular, performs a convolution over poloidal modes due to the inseparable character of the wave equations in this direction. The structure of the poloidal wave propagation is observed to vary with physical plasma parameters, caused by the relative phasing of forward and reflected waves between the antenna and the resonance zone. Significant alteration of the spectral dependence of the loading resistance accompanies this phenomenon. The wave equations are integrated over a sufficiently wide $k_{\parallel}$ spectrum so as to be able to accurately characterize a localized antenna current distribution.

Effects from variation in a variety of relevant experimental parameters have been studied, including density, temperature, minority species concentration, and antenna shape. We present results from a study of ICRF heating in TFTR-like plasma conditions, which indicate the presence of partially damped standing waves in the plasma response.

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

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ANOMALOUS CURRENT PENETRATION AND OSCILLATING CURRENT DRIVE IN TOKAMAKS

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A current drive scheme for tokamaks, involving oscillating the OH circuit, is proposed. This scheme is based upon the experimentally observed anomalous skin penetration during the startup phase of tokamaks. This behavior is generally attributed to double tearing modes which can be destabilized by the double-valued q profiles present in skin current profiles. Analytic and numerical results indicating feasibility are shown and scaling of steady state current and power dissipated with frequency and plasma resistivity is presented. These results are obtained using a one-dimensional model in which the double tearing mode activity is idealized by helicity conserving relaxations which occur in the part of the cycle when the skin current is parallel to the main current. It is shown that any resistive MHD activity responsible for anomalous current penetration, and therefore required for the success of this current drive scheme, must be fully three dimensional, i.e., multiple helicity. Finally, a comparison of the effectiveness of this scheme with that of F-θ pumping in RFP's is presented. This comparison indicates that there is no advantage to be gained by oscillating the toroidal field in the tokamak.

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

RF Heating and Cyclotron Instability*

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Non-inductive current drive, auxiliary heating, formation of energetic particles and of electrostatic potentials are some of the uses envisaged for rf waves in fusion plasmas. The bandwidth of the sources of radiation currently employed in many experiments is so narrow that a formulation of quasilinear theory based on particle interaction with coherent waves is necessary. An interesting and novel feature of such a calculation is its prediction regarding the motion of particles along the field lines. In particular, it is shown that the phase space of trapped particles is divided into two parts. In one, as a particle gains energy its turning point moves towards the region of weaker magnetic field; in the other, energy gain results in the turning point moving towards the region of stronger magnetic field, with eventual detrapping. Specializing to the case of electrons, for rf field amplitudes well above the threshold for stochasticity, the diffusion coefficient for the Fokker-Planck operator has been derived, including the effects of relativity, finite parallel wavenumbers and spatial localization of the rf waves. Superadiabaticity of particle motion has been studied. A bounce-average quasilinear operator describing cyclotron-instability-induced diffusion of electrons has also been derived, and the form of a steady-state distribution function under the joint action of heating and instability obtained. Insertion of the distribution function into the dispersion relation for the cyclotron waves yields a relation between the energy density in the rf waves and that of the saturated state of the cyclotron instability.

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

ANOMALOUSLY LARGE T_i/T_e RATIOS DUE TO ExB DRIVE

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Anomalously large T_i/T_e ratios have been observed in the Burnout IV experiment at[1] ORNL (300+) and in the 19-ft. long magnetically confined carbon arc (100). These hot ion plasmas are believed due to radial electric fields ($E_r \sim -7$ kV/cm and ~ -1 kV/cm, respectively) in axial magnetic fields ($B_z \sim 29$ kG and 15 kG, respectively), which lead to strong ExB drive of the ions with ions or electrons gaining drift energies proportioned to their masses. The drift velocity is

$$v_{d,\ i\ or\ e} = c\ (ExB/B^2)/(1 + a/r_o + a^2/2r^2_0),$$

where $c = 10^8$ cm/sec when E is in volts/cm and B in gauss, and where a is the ion or electron gyro-radius due to ExB drive and r_o is the distance at which d^2r/dt^2 is zero. The time scale for ExB drive is much faster than particle diffusion times (τ_{ee}, τ_{ie}, τ_{ii}) and leads to rapid stochastic promotion of slow electrons out of the dominant stopping power energy loss region for the ions into the 100-fold lower non-dominant energy loss region ($v_e > v_i$)[1]. Scatter events lead to a hot ion thermal distribution admixed with the average ion drift energy and "T_i" > T_e. In a nuclear electromagnetic dynamo this should permit efficient burning of advanced fusion fuels.[2] Nuclear safety considerations should be given serious consideration.

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NEOCLASSICAL LIKE IMPURITY TRANSPORT IN CENTRAL REGION OF TOKAMAK THEORY VERSUS EXPERIMENT

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Using soft x-ray imaging, simultaneous absolute density profiles of carbon (plateau regime) and molybdenum (Pfirsch Schluter regime) have been determined in Alcator C[1]. After pellet injection, the sawtooth behavior changes to a slow buildup of a "giant impurity disruption". During this time, the impurities peak strongly in the center, qualitively reminiscent of J.B. Taylor's result

$$n_z(r)/n_z(o) = [n_i(r)/n_i(o)]^z \qquad (1)$$

but quantitatively different.

Quantitative neoclassical impurity transport analysis for this multi-species mixed collisionality regime situation has been performed: Carbon diffusion is mainly driven by $\partial T/\partial r$ (i.e. thermal friction), molybdenum diffusion by $\partial n_C/\partial r$ (i.e. friction on carbon.) Appropriate generalizations of Eq. (1) are derived. The experimental profiles are near transport equilibrium, and in the core region, the particle source terms are negligible, permitting an approximate solution of the particle conservation equations for the radial impurity profiles. Thus D_j/V_j can be determined (where D_j and V_j are defined through $\Gamma_j = -D_j \ \partial n_j/\partial r - n \ V_j$, j = C, Mo), but lacking time dependent measurements, D_j and V_j cannot be separately determined. The calculated profiles are close to the experimental ones.

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

Abstract for Submission to
1986 Sherwood Theory Conference
April 14–16, 1986
New York, New York
Annual Controlled Fusion Theory Conference

STABILITY OF A ONE-DIMENSIONAL PLASMA IN SLAB GEOMETRY*

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Stability of a plasma in a one-dimensional (1-D) slab geometry equilibrium is considered. Considerations are limited to the simplest case — that for which the plasma pressure as well as the plasma flow vanish and the magnetic field is almost uniform (tokamak ordering). We consider special continuous deformations of such equilibria. The deformations, which are similar to those of the tearing mode, satisfy a form of the ideal MHD constraints conjectured relevant, and the energy is never increasing along the path of the deformation. The deformed configurations are not equilibria. It is found that unless the initial equilibrium is a Taylor configuration, configurations of lower energy exist along the path. This is interpreted to mean that among the 1-D slab geometry plasmas, only the Taylor equilibrium is stable. The calculations are so simple that they are carried out without linearization. Therefore, it may not be too surprising that the result obtained differs from that of linear tearing mode theory.

*This work supported by U.S. Department of Energy Contract #DE-AC03-84ER53158.

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Dynamics of L–H Transition*

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It has been convincingly demonstrated[1] in ASDEX that the temporal transition from L to H plase during neutral beam injection into a diverted tokamak plasma is initiated by the sudden formation of a transport barrier in a thin edge region inside the separatrix. Similar transitions also have been observed in DIII for marginally diverted discharges, where the edge confinement improvement is accompanied by a reduction in magnetic probe signals.

We postulate that the critical edge condition for the barrier formation is the temperature gradient exceeding a threshold.[2] A number of observations pertaining to the circumstance of the occurrence of the transition, such as power thresholds, density thresholds and transition time after NBI, can then be qualitatively understood. Stabilization[3] of drift waves by η_e or η_i with no trapped particle effects is a plausible cause of the transition.

The transport properties of the edge barrier are investigated both analytically and numerically by solving simple transport equations and comparing the results with various temporal signals. Convective energy loss is shown to play an important role in determining the relative merits of open and closed divertor configurations.[4] It appears possible to explain the improvement of overall energy confinement by the effect of the barrier alone without requiring any change in the transport mechanism in the interior.

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*This is a report of work sponsored by the Department of Energy under Contract No. DE-AC03-84ER51044.

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APPLICATIONS OF NEUTRALIZED ION BEAMS TO MAGNETIC FUSION

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Pulsed ion beams may be used for plasma heating and current control. The unique features are that high particle energy and high current density are easy to obtain. Pulsed ion beams from magnetically insulated diodes are neutralized by picking up electrons from any source. The ions together with an equal number of co-moving electrons constitute a beam with no net charge or current. It can propagate across a magnetic field with no deflection[1] if the current density is sufficiently large to satisfy the condition $4\pi nMc^2/B^2 > (M/m)^{1/2}$, where n is the density of ions of mass M, m is electron mass and B is the magnetic field. The transport is accomplished because of electric polarization that produces an electric field $\underset{\sim}{E}$ so that the beam crosses the field by means of $\underset{\sim}{E} \times \underset{\sim}{B}$ drift. This process is well understood and documented. If the beam traverses a plasma as well as a transverse magnetic field, the polarization may be drained in which case the beam reverts to single particle motion. This process is not well understood but has been observed and discussed. Methods for trapping a neutralized ion beam in tokamak or mirror geometry will be discussed as well as preliminary experimental results.

Conventional neutral beams have been quite important for contemporary magnetic confinement experiments. However, they are limited to particle energy of about 100 kev and current density of .1 A/cm^2. Removing these limitations leads to many technical advantages for reactor scale tokamaks. In addition there are reactor configurations obtained by injecting beams into tokamak or mirror geometry that involve much higher beam particle energy and current density. The confinement geometry is that of a modified Betatron. In this configuration an energy gain per beam particle of a factor of about 20 is possible for D-T reactions,[2] whereas previous studies of beam-target interactions predicted a maximum[3] energy gain of about 4. It is thus worthwhile to consider a small fusion reactor without ignition. The high beam energy is also essential for advanced fuel reactors.

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MONTE CARLO SIMULATION OF ALPHA-PARTICLE TRANSPORT IN TANDEM MIRRORS*

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A code has been developed to study the transport of fast ions in the center cells of tandem mirrors. Trajectories are computed using the guiding-center approximation with azimuthal drift arising from finite-β effect depression of the magnetic field and radial drift coming about because of radial gradients in the hot-ion drag on electrons and warm ions. Collisions are incorporated with Monte-Carlo simulation of the Spitzer collision terms. The code has been applied to heating of reactor plasmas by alpha-particles. Particle and energy losses to the wall, halo, loss-cone, as well as energy transfer to ions and electrons are computed. We have found a substantial dependence of the radial distribution of energy deposition on the background density and temperature profiles. Representative results are given.

*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.

SHERWOOD THEORY MEETING 1986

The $m = 1$ MHD Instability in Tokamaks*

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Recent results on TEXT have shown that the sawtooth crash has an $m = 1$ structure with growth rate much larger than the usual $m = 1$ precursor, which may or may not be present, and the results suggest an MHD interchange mode. Also, a study of sawtooth properties in ohmically-heated tokamaks reveals two distinct classes. (a) In the smaller tokamaks, where the impurity ions are in the Pfirsch-Schluter regime, the precursor's real frequency is typically 5–10 kHz and is explained by the poloidal rotation predicted by neoclassical theory. In addition, the poloidal rotation satisfies $V_\theta(\equiv -E_r/B) = (B_\theta/B)\, v_{Tz}$, where v_{Tz} is the thermal velocity of the heaviest significant impurity present. In fact, the neoclassical condition for V_θ to reach this value accurately predicts T_{eo} for such discharges. (b) In the larger Tokamaks (TFTR, JET), where the z-ions are in the plateau regime, the $m = 1$ frequency is ~ 1 kHz, which is still explained by the neoclassically predicted V_θ. But V_θ is an order of magnitude less than $(B_\theta/B)\, v_{Tz}$. For the conditions of (a), the pressure on a magnetic surface satisfies $p = \bar{p} + \tilde{p}_c \cos\theta$, where $\tilde{p}_c = 4n_z T_i V_\theta^2 (r/R) \Big/ \left[(B_\theta/B)^2 v_{Tz}^2 - V_\theta^2 + i\sqrt{2} r \nu_{ii} Z^2 V_\theta \,(m_i/m_z) \right]$. Since $\partial p_c/\partial r > 0$ for $V_\theta < B_\theta v_{Tz}/B$, its interaction with the toroidal field curvature is stabilizing, but this changes abruptly to destabilizing as the resonance in $\tilde{p}_c$ is passed. Also the important side band modes, $m \pm 1$, undergo a resonance enhancement for the same V_θ as in $\tilde{p}_c$. An MHD mode is predicted for $V_\theta > B_\theta v_{Tz}/B$. With the z-ions in the plateau regime there is no such dramatic resonance. $\tilde{p}_c = \left(\sum_{i,z} n_j m_j\right) \left(rB^2/RB_\theta^2\right) \left(V_\theta^2 - V_\theta U_{pj}\right)$, where $U_{pj} = -\partial \bar{p}_j / \partial r / n_j Z_j e B$, and $\partial \tilde{p}_c / \partial r < 0$ for $\sum n_j m_j U_{pj} > \sum n_j m_j V_\theta$.

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

SIMULATION OF RAMPED CURRENT OPERATION IN THE REVERSED-FIELD PINCH*

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One of the more interesting experimental RFP observations occurs in "ramp shots"; discharges in which the toroidal current is slowly increased after startup and field reversal. The plasma is observed to generate toroidal flux and maintain field reversal in such a way as to retain approximately constant values of F and Theta. Since the axial field is reversed at the wall before the current ramp begins, toroidal flux can increase only by expelling negative flux from the plasma. The continued maintenance of field reversal in the presence of negative flux expulsion is referred to as the RFP dynamo. We simulate this process with a 3D MHD code by applying an axial voltage that increases linearly with time, and a poloidal voltage to maintain constant Theta in the presence of increasing current. As in the experiment, we find that field reversal is maintained as the current doubles. Negative axial flux is generated in sufficient amounts to compensate for that withdrawn by the poloidal circuit; the corresponding generation of an equal amount of positive flux accounts for the flux increase. Long wavelength MHD modes are responsible for this dynamo action.

An analysis of these results is presented wherein the symmetric part of the poloidal voltage as a function of radius is decomposed into its constitutive parts. The implications of this work on RFP theory is discussed.

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*Work supported by the USDOE.

♦Named for Capital City of France.

INFLUENCE OF ANOMALOUS THERMAL LOSSES ON IGNITION CONDITIONS*

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In the process of achieving ignition conditions, microinstabilities, which lead to anomalous thermal transport of the fusing nuclei, are likely to be present. When such phenomena are taken into account, an appropriate formulation of ignition criteria becomes necessary. In particular, a new type of plasma density limit is identified.

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

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Thermal Effects on Tearing Modes*

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Thermal instabilities play an important role in the growth of magnetic islands and the stochasticity of the field lines. In usual tokamaks, where shear is positive, the tearing islands can grow and may cause the plasma to disrupt when the islands are cooled.[1]

Numerically, the islands are found to be growing when the islands are cooled. In this case, they tend to grow inward toward the magnetic axis, because the shear is weaker on the inside. Inclusion of thermal effects in the edge region, between islands and the wall, causes the islands to grow toward the wall significantly. The thermal effect in this edge region is based on the assumption that the region is stochastic due to the mode coupling. When the thermal effects on both the inside and the edge region are considered, the islands can grow in both directions.

The numerical results and the mechanism of the thermal effects on tearing modes will be discussed.

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

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RELAXED STATES IN REVERSED-FIELD PINCHES AND TOKAMAKS*

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It is well-known that turbulent fluctuations can produce a d.c. electric electric field $\vec{F} = \langle \vec{v} \times \vec{b} \rangle$ which drives slowly varying profiles in a toroidal plasma. We present exact results on $\vec{F}$ for tearing and resistive interchange modes, including the effects of compressibility, and show that they have remarkable consequences for relaxed states in RFP's and Tokamaks.

The problem of resistive interchange modes is reformulated. It is shown that previous work/1/, which has resulted in popular scaling laws favorable for RFP's, is incorrect. In particular, it is shown that the incorrect set of equations/1/, due to the existence of additional groups of transformations, actually gives zero diffusion. We solve the problem exactly in a low-pressure, weak-shear limit to obtain an analytic expression for $\vec{F}_{\perp}$. This component determines primarily the plasma beta and the pressure profile.

We compute $\vec{F}$ from the boundary-layer equations of tearing modes. It is shown that $\vec{F}_{\parallel} = \vec{B}/B^2 \, \mathrm{div}(k^2 \, \mathrm{grad} \, \lambda)$, where $\lambda = \vec{J}.\vec{B}/B^2$ and k^2 is a positive function. An explicit expression is obtained for k^2, and its positivity is proved from the layer equations for purely growing modes.

Steady state solutions for RFP's in the presence of an external electric field, is computed. It is shown that even a small value of k^2 is sufficient to take an RFP plasma to a field-reversed Taylor state, however, with finite pressure gradients. The fraction of the power driving fluctuations to the ohmic power is shown for a typical relaxed state to be approximately 30%, in striking agreement with ZT-40 observations/2/.

Tokamak-like solutions are also computed from the same steady-state equation, with different boundary conditions. Relaxed states for Tokamaks are seen to have certain universal properties. Implications for 'profile consistency' will be discussed.

* Work supported by US DOE DE-FG02-86ER53222

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SHERWOOD THEORY MEETING 1986

The Intrinsic Electromagnetic Solitary Vortices in Magnetized Plasma*

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Several Rossby-type vortex solutions constructed for electromagnetic perturbations in magnetized plasma encounter the difficulty that the perturbed magnetic field and the parallel current are not continuous on the boundary between two regions. We find that fourth order differential equations must be solved to remove this discontinuity. Special solutions for two types of boundary value problems for the fourth order partial differential equations are presented. By applying these solutions to different nonlinear equations in magnetized plasma, the intrinsic electromagnetic solitary drift-Alfvén vortex (along with solitary Alfvén vortex) and the intrinsic electromagnetic solitary electron vortex (along with short-wavelength drift vortex) are constructed. While still keeping a localized dipole structure, these new vortices have more complicated radial structures in the inner and outer regions than the usual Rossby wave vortex. The new type of vortices guarantees the continuity of the perturbed magnetic field $\delta \mathbf{B}_\perp$ and the parallel current $j_\parallel$ on the boundary between inner and outer regions of the vortex. The allowed regions of propagation speeds for these vortices are analyzed, and we find that the complementary relation between the vortex propagating speeds and the corresponding phase velocities of the linear modes no longer exists.

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

A NUMERICAL STUDY OF STELLARATOR TRANSPORT

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A detailed study of transport at low collision frequencies has been performed, using a numerical method of solution of the bounce-averaged Fokker-Planck equation which describes both ripple-trapped and non-ripple-trapped particles in a stellarator. Standard and "Transport-Optimised" Stellarators are studied, the latter for the first time at collision frequencies low enough that the effect of a radial electric field is important. Although existing analytic methods of solution can strictly only be applied in rather limited regions, some extensions of analytic results are discussed which enable us to quantitatively explain the behaviour observed.

The scaling of D with E_r in a standard (ATF-like) device appears to agree very closely with the predictions of certain analytic theories, being as E_r^{-2}, $E_r^{-3/2}$, E_r^{-1} and E_r^{0} in the various "regimes" of transport which have tentatively been identified. In the same cases D scales with ν as ν^1, $\nu^{1/2}$, ν^0 and ν^{-1}, from the lowest to the highest collision frequencies.

The "transport-optimised" devices which showed improved transport properties in the $1/\nu$ regime seem to exhibit a similar behaviour down to very low collision frequencies (where the transport eventually becomes faster than "usual".) This is not what was originally expected by some authors. A possible explanation of this result is given.

The calculations appear to agree very closely with the results of a "hybrid" bounce-averaged/guiding-centre Monte Carlo code[1].

1 C.D. Beidler, W.N.G. Hitchon and J.L. Shohet, "Numerical Study of Ripple Transport in a Transport Optimized Stellarator Field", (this Conference).

NUMERICAL STUDY OF RIPPLE TRANSPORT IN A "TRANSPORT OPTIMIZED" STELLARATOR FIELD

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A "hybrid" bounce-averaged/guiding center Monte Carlo numerical simulation is used to examine particle transport in the model stellarator field

$$B = B_0(1 + \varepsilon_t \cos\theta - \varepsilon_h(1 + \sigma \cos\theta) \cos(\ell\theta + p\phi))$$

where σ is a constant, $|\sigma| < 1$, and other symbols have their usual meanings. This model field was first examined in the most collisional of the low frequency regimes[1]. In this regime it was shown that $\sigma > 0$ provides reduced transport over that obtined for the usual model field ($\sigma = 0$), while $\sigma < 0$ produces increased transport rates. In the present work, we have examined the lower collision frequency regimes not previously handled and have also included the effects of the strong radial electric field expected to be present in a stellarator at these collision frequencies.

The numerical method employed rapidly and accurately describes the orbits of ripple trapped particles in the given model field. This is especially important for these transport optimized ripple profiles as the particle orbits are substantially different from those assumed in the usual analytic theory and allowed for in other numerical simulations except guiding center codes.

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SHERWOOD THEORY MEETING 1986

Axisymmetric MHD-Stable Sloshing Particle Distribution Functions*

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Plasmas in axisymmetric mirror devices can be made stable to the MHD interchange mode by introducing "sloshing ions" which spend a sufficiently large fraction of a bounce time in regions of good curvature so that one achieves pressure weighted stability. Pitch angle scattering adversely affects the method by reducing the favorable weighting.[1] By using a stationary energetic ion beam distribution F_b obtained from solutions of a Fokker-Planck equation[2] accounting for drag and pitch angle scattering, we have calculated the possible energies of the energetic ions and the corresponding magnetic field configurations required for stabilization. Stabilization is obtained by tailoring the values of the magnetic variation so that the MHD perturbed energy for an $m = 1$ flute mode

$$\delta W \equiv \int dB \frac{B'}{B^{3/2}} \frac{d}{dB} \left(\frac{P}{B^{3/2}} \right) > 0.$$

Here, $P = P_\perp + P_\parallel$ is the pressure, B the strength of the magnetic field, and B' is the derivative of B with respect to the coordinate along the field line. If for simplicity we choose $\frac{B'}{B^{3/2}}$ as piecewise constant, with a value $\frac{B'}{B^{3/2}} = \frac{1}{B_0^{1/2}} \frac{1}{L_1}$ for $1 < \frac{B}{B_0} < R_{\text{eff}}$ and $\frac{B'}{B^{3/2}} = \frac{1}{R_{\text{eff}}^{1/2} B_0^{1/2}} \frac{1}{L_2}$ for $R_{\text{eff}} < \frac{B}{B_0}$, ($B_0$ is the midplane value of B) stability requires

$$\left[\left(P/B^{3/2} \right)_{R_{\text{eff}}} - \left(P/B^{3/2} \right)_{B_0} \right] (L_2/L_1) > \left(P/B^{3/2} \right)_{R_{\text{eff}}} \left(1/R_{\text{eff}}^{1/2} \right)$$

where $\left(P/B^{3/2} \right)_{R_{\text{eff}}}$ is the value of $P/B^{3/2}$ at $B = B_0 R_{\text{eff}}$. Stability can be achieved if $(P/B^{3/2})_{R_{\text{eff}}} > (P/B^{3/2})_{B_0}$. The Fokker-Planck calculation shows that the condition can be achieved if E_b/T_e is greater than 200, where E_b is the injection energy and T_e the electron temperature. For $E_b/T_e \approx 1000$, we find MHD stability is possible for $L_2/L_1 \approx 3$, a moderate scaling factor. This principle can be tested with present day neutral beam and mirror machine technology ($E_b \sim 20 - 100$ keV, $T_e \lesssim 100$eV). In reactors, neutral beams of several MeV will be needed to make use of sloshing ion stabilizing mechanism.

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

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SHERWOOD THEORY MEETING 1986

Anchor Stabilization of Trapped Particle Modes in Mirror Machines*

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It is shown that for trapped particle modes in tandem mirrors, the pressure of the passing particles in the anchor region introduces a stabilizing term proportional to the sum of the anchor's field line curvature and total *diamagnetic pressure.* The self-well effect was not realized in previous analyses. The theory is applied to the proposed gas dynamic trap experiment at Novosibirsk. We show that by varying the mirror ratio, which can be as large as 80, one can go from regimes where the trap particle mode is stable to regimes where it is unstable.

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

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SHERWOOD THEORY MEETING 1986

The Trapped Particle Effect on Diamagnetic Limit in Hot Electron Physics *

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Previous analysis in cylindrical geometry with an artificial curvature drive showed that instability of the precessional mode arises just below the formation of a magnetic well by a hot electron ring. This instability arises because the stabilizing dissipative resonance response of hot particles at the outer edge disappears as drift reversal is approached. However, in a mirror configuration the disappearance of the resonance interaction of particles in the outer edge is governed by the drift reversal condition for the hot particles with the largest pitch angle. Thus, a modification to the predicted threshold of the precessional mode is expected. The calculation in a bumpy cylinder with small mirror ratio shows that stability to the precessional mode can exist for $\varsigma < 2$ (ς, the drift reversal parameter, is defined as $\beta_{\perp h}/2\Delta\kappa$ with $\beta_{\perp h}$ the hot pressure beta, Δ the hot electron layer thickness, and κ the field line curvature at the midplane). Numerical results are presented for parameters related to the EBT and SM-1 experiments.

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

POSSIBLE CANDIDATE MICROINSTABILITY FOR ANOMALOUS ELECTRON TRANSPORT*

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A possible microinstability associated with the plasma current density and the dependence of the electrical resistivity on the particle density is presented. This circumstance occurs in the region of the plasma column where the effects of trapped particles tend to become important, if the collisional form of the resistivity is considered. Hence the growth rate that is found depends on the electron-ion and electron-electron collision frequency as the longitudinal electron thermal conductivity contributes to the mode stability for realistic values of $\eta_e = (d\ell nT_e/dr)/(d\ell n n/dr)$. The effect of magnetic shear is taken into account and the solution of the appropriate dispersion equation is analyzed.

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

SUPPLEMENTARY PROGRAM

THEORETICAL MODEL OF FISHBONE OSCILLATIONS

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We present a model[1] for the excitation of fishbone oscillations in beam-injected plasmas where: (1) the excited m=1 mode has a frequency related to the core-ion diamagnetic frequency ω_{di} (at the q=1 surface) and is one of the two marginally stable modes predicted by the finite Larmor radius theory of m=1 modes when the ideal MHD condition for instability is satisfied; (2) the source of free energy is related to the total plasma pressure gradient; (3) the presence of a "viscous" dissipative process (e.g. produced by a mode-particle resonance) is required to let this mode go unstable. The model dispersion relation can be put in the form

$$[\omega + i\nu(\omega)]\ (\omega - \omega_{di}) = -\gamma^2_{MHD}$$

where γ_{MHD} is the growth rate of the ideal pressure driven internal kink mode which, with $\nu(\omega)=0$, is marginally stabilized in the relevant limit $\omega_{di} > \gamma_{MHD}$; $\nu(\omega) = \alpha\omega^2/(\omega-\omega_{di})$, with $\alpha \sim (m_h n_h/m_i n_i)(R/r_{p,h})$, r_p the pressure gradient length and "h" referring to hot beam particles, represents the rate of resonant momentum exchange between trapped beam particles with magnetic drift frequency $\omega^{(0)}_{Dh}(\varepsilon,\mu)$ and the mode. The resonance is more effective for the root with $\omega \sim \omega_{di}$, as $\omega_{di}/\omega^{(0)}_{Dh} \sim (T_i/T_h)(R/r_{n,i})(1+\eta_i) \sim 1$ for typical beam temperatures (for PDX, $\omega_{di} \gtrsim 15$ kHz). The resulting growth rate is $\gamma \gtrsim \alpha|\omega_{di}| > 1\ ms^{-1}$, consistent with the observed time over which resonant beam particles are ejected as a byproduct of the excited instability. This resonant loss also provides the saturation mechanism, by temporary removal of the dissipative process, required to explain the full fishbone cycle. The excited mode also leads to a local flattening of the plasma pressure gradient near the q=1 surface; the corresponding decrease in ω_{di} may explain the observed drop of the mode frequency during a fishbone burst. The effects of resistivity and finite hot particle banana orbit are also discussed. This model is alternative to that of Ref. 2.

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SUPPLEMENTARY PROGRAM

The Global MHD for Circular and Highly-Elongated Tokamaks With Magnetic Separatrices

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The pressure and current driven global MHD stabilities are examined by using a new initial value code CART for circular and highly-elongated tokamaks with and without magnetic separatrices. The role of the extreme magnetic shear due to the presence of a magnetic separatrix was found to be very weak in modifying the essentially ideal finite-beta external kink mode characteristics as long as the pressure and current-density profiles are the same. For the case with a separatrix, the open magnetic fields in the vacuum region was found to substantially reduce the unstable mode's growth rate through the line-tying effect only when the vacuum resistivity is finite and small. Several tokamak equilibria with large elongation ($E = 4$, 6, and 8) were examined by using the CART code against n=0, 1, and 2 modes. For the bean-shaped case with $E = 6$ and $\beta_p = 0.075$, the n=0 mode is stable for a conforming conducting wall distance D/a less than 0.27, while the n=1 and n=2 modes are stable for $D/a \leq 0.08$. For the racetrack case with $E = 6$ and $\beta_p = 0.1$, the n=0 mode is stable for $D/a \leq 0.28$, but remains unstable even with the wall at the plasma boundary. The grid-convergence was reasonably good for three different numbers of grid spaces (64×256, 64×128, 32×128, and 16×64). The various stabilizing schemes were also considered; a toroidal limiter covering 20% of the plasma circumference reduces the growth rate by a factor of five for both n=0 and n=1 modes.