FUSION RESEARCH CENTER

ANNUAL CONTROLLED FUSION

THEORY CONFERENCE

April 8-10, 1981

Austin, Texas

THE UNIVERSITY OF TEXAS

Austin, Texas

ANNUAL CONTROLLED FUSION

THEORY CONFERENCE

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Sponsored by

Fusion Research Center
and
Institute for Fusion Studies
University of Texas at Austin
Austin, Texas 78712

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General Information

All oral sessions will be held in the LBJ Auditorium, located in lower level of the LBJ library.

All poster sessions will be held in the Joe C. Thompson Conference Center. There will be two consecutive poster sessions on Wednesday and Thursday afternoons, and one poster session Friday afternoon.

Registration will take place at the Villa Capri Hotel from 7:00 P.M. to 10:00 P.M. on Tuesday, April 7 and at the LBJ library from 8:00 A.M. to 10:00 A.M. on Wednesday, April 8. Assistance will be available for travel and other problems at the Thompson Center and LBJ auditorium throughout the conference. A cash bar will be available at the Villa Capri Tuesday evening.

There have been 267 papers submitted, of which 21 were selected for oral presentation. Those giving talks may, at their option, present posters the afternoon following their talk.

SCHEDULE

Tuesday, April 7

7:00 - 10:00 p.m.	Registration and Cash Bar

Wednesday, April 8

8:20	Welcome
8:30 - 12:15	Oral Session 1A
(10:30 - 10:45)	Coffee Break
12:15 - 1:30	Lunch
1:30 - 3:15	Poster Session 1B
3:30 - 5:15	Poster Session 1C

Thursday, April 9

8:30 - 12:15	Oral Session 2A
(10:30 - 10:45)	Coffee Break
12:15 - 1:30	Lunch
1:30 - 3:15	Poster Session 2B
3:30 - 5:15	Poster Session 2C

Friday, April 10

8:30 - 12:15	Oral Session 3A
(10:30 - 10:45)	Coffee Break
12:15 - 1:30	Lunch
1:30 - 3:15	Poster Session 3B

Refreshments will be available continuously during the poster sessions.

1981 SHERWOOD MEETING
Annual Controlled Fusion Theory Conference
April 8-10, 1981 -- The University of Texas -- Austin, Texas

Tuesday, April 7

7:00-10:00 PM Registration and Cash Bar
Villa Capri Hotel

Wednesday, April 8

8:00-10:00 AM Registration at LBJ Auditorium
(Assistance will be available throughout the conference.)

8:20 AM Welcome
LBJ Auditorium

1A 8:30 AM ORAL SESSION
LBJ Auditorium
J. R. Drake and B. McNamara, Chairmen

1A1. EBT Stability Theory. H. L. Berk, M. N. Rosenbluth, and J. W. Van Dam.
1A2. The Motion of a Charged Particle in a Magnetic Field with Nearly Helical Symmetry. J. A. Tataronis and H. Weitzner.
1A3. Plasma Properties in Poloidal Divertors. M. Petravic, D. Heifetz, D. Post, J. Schmidt, and G. Petravic.
1A4. Simulation of Islands in Tokamaks. O. Betancourt, P. Garabedian, and M. Marcal.

10:30-10:45 AM Coffee Break

1A5. Breakdown of Onsager Symmetry in Neoclassical Transport Theory. K. Molvig, L. M. Lidsky, K. Hizinidis, I. B. Bernstein, and K. Swartz.
1A6. A Survey of Fluctuation Measurements in Tokamaks and Comparison with Various Theories of Anomalous Electron Transport. P. C. Liewer.
1A7. Prospects for Fusion Plasma Theory. D. B. Nelson.

12:15-1:30 PM Lunch

1B 1:30-3:15 PM POSTER SESSION
(plus optional posters from Oral Session 1A)
Thompson Conference Center

1B1. Guiding Center Orbits in Stellarators. R. A. Schill, Jr. and J. L. Shohet.
1B2. Neutral Beam Effect on Ballooning Mode Stability. R. R. Dominguez, R. L. Miller, and T. Ohkawa.
1B3. The Radial EBT Stability Problem. A. M. El Nadi and K. T. Tsang.

1B4. Numerical Study of Torus II. R. Izzo and C. K. Chu.
1B5. Boundary Layer Corrections on Neoclassical Ripple Transport in Tokamaks. K. C. Shaing and J. D. Callen.
1B6. Ambipolarity of Particle Flow Due to Magnetic Fluctuations and Charge Filamentation Instabilities. R. E. Waltz.
1B7. The Influence of finite Gyroradius and Resistivity on the Alfven Wave Continuum. W. M. Tang, J. B. Taylor, and J. W. Connor.
1B8. Numerical Computation of Resistive Instabilities in a Torus. A. H. Glasser.
1B9. Plasma Heating From Upper Hybrid Mode Conversion in an Inhomogeneous Magnetic Field. A. T. Lin, C-C. Lin, and J. M. Dawson.
1B10. Limiting Beta of l=2 Stellarators With no Net Current. H. R. Strauss and D. A. Monticello.
1B11. Monte-Carlo Heating Simulations of PDX and PLT. A. M. Todd, F. H. Tenney, and M. Okabayashi.
1B12. Resonant Helically Distorted Relativistic Electron Beam Equilibria for Free Electron Laser Applications. R. C. Davidson and G. L. Johnston.
1B13. Single charged Particle Motion in Tokamak Geometries. H. Weitzner.
1B14. Hybrid Simulation of Ion Beams and Rings in Background Plasma. A. Mankofsky, R. N. Sudan, and J. Denavit.
1B15 Current Generation by Electron Cyclotron Wave in a Toroidal Device. V. S. Chan, S. C. Chiu, J. Y. Hsu, and S. K. Wong.
1B16 Tokamak Plasma Heating Using Energetic Ion Beams. F. L. Hinton and J. C. Wiley.
1B17. Rotational Instabilities in Field-Reversed Configurations; Results of Two-Dimensional Hybrid Simulations. D. S. Harned.
1B18. D-D tokamak Reactor Modeling. D. C. Baxter, R. N. Byrne, J. B. McBride, S. Tamor, and C. E. Wagner.
1B19. Equilibrium and Transport of a Compact Toroid. A. Sgro, R. Spencer, and C. Lilliequist.
1B20. Lower Hybrid Drift Instability; Theory and 2d Simulations. Y-J. Chen, C. K. Birdsall, and W. M. Nevins.
1B21 Mechanisms for Energy Transfer from Electrons to Ions in Tokamaks. A. A. Ware.
1B22. Effect of Pitch-Angle Collisions and Phase Decorrelation on DCLC Transport in a Mirror Machine. B. I. Cohen, R. H. Cohen, and T. D. Rognlien.
1B23. Role of Magnetic Helicity on the Evolution of the Most Probable Equilibrium Profiles for the Reversed Field Pinch. A. Punjabi, G. Vahala, C. Smith, and W. H. Matthaeus.
1B24. Wave-Driven Currents in a Torus. C. D. Boley and D. A. Ehst.
1B25. Wave Enhanced Production of Runaway Ions in Tokamak Plasmas and Its Implication for a Two-Component Reactor. Z. G. An, Y. C. Lee, and C. S. Liu.
1B26. Magnetic Trapped Particle Modes. M. N. Rosenbluth.
1B27. Symmetries and Preferred Constants of the Motion. E. Hameiri.
1B28. Magnetic Field Errors in the RFP From Poloidal Flux Gaps. R. Spencer, R. A. Gerwin, and T. Hewitt.
1B29. Simulation of the Quasi-Static Formation of a Spheromak Using Combined Z- and Theta-Pinch Techniques. A. Bondeson.
1B30. Electron Currents Effects in Field-Reversed Mirror Dynamics. R. A. Stark, G. H. Miley, and T. Haill.
1B31. Gyroelastic Fluids. G. D. Kerbel and W. A. Newcomb.
1B32. Drift Mode Analysis of the Tandem Mirror. W. Horton.
1B33. Scaling Laws for Beam Heated Field Reversed Mirrors. B. McNamara, S. P. Auerbach, and J. K. Boyd.
1B34. Effect of turbulent diffusion on collisionless Tearing Instabilities. J. D. Meiss, P. H. Diamond, S. M. Mahajan, and R. D. Hazeltine.
1B35. Internal Kink and Collisionless Magnetic Reconnection In Finite-Beta Toroidal Plasmas. G. B. Crew, J. J. Ramos, and L. Sugiyama.
1B36. Kinetic Effects on the Tilting Mode in Field Reversed Configurations. C. E. Seyler and D. C. Barnes.
1B37. Nonadiabaticity in an Axisymmetric Mirror With an Internal Ring. E. A. Adler.
1B38. MHD Equilibrium and Stability of Axisymmetric Tandem Mirror Plug with an Internal Ring. A. E. Walstead and E. A. Adler.
1B39. Consolidated Continued Fraction Technique for Solving the Direct Interaction Approximation. H. A. Rose.

1B40. Effects of a Strong Mean Magnetic Field on MHD Turbulence. D. Montgomery and L. Turner.
1B41. On a Helical Ohmic State for Reversed-Field Pinches. R. Y. Dagazian.
1B42 EBT Transport and Ambipolar Potential Formation with Rapid Loss of High Energy Impurity Ions. E. F. Jaeger, R. K. Richards, and C. L. Hedrick.
1B43. Stability Analysis of Straight Stellarators. S. Yoshikawa and R. M. Kulsrud.
1B44. A Moments Approach to Free Boundary Two-Dimensional Tokamak Transport and Axisymmetric Resistive Stability. K. M. King and S. C. Jardin.
1B45. Synchrotron Radiation Emission from an Anisotropic Electron Distribution Function. C. M. Celata.
1B46. Theory of Flux Amplification in Plasma Gun Produced Compact Toroids. J. H. Hammer.
1B47. Like-Particle and Test-Particle Transport. R. H. Cohen, K. Molvig, and I. B. Bernstein.
1B48. The Role of "Passing" Electrons in the Energy Balance of Tandem Mirror Plasma. D. L. Galbraith and T. Kammash.

1C 3:30-5:15 PM POSTER SESSION
Thompson Conference Center

1C1. Renormalized Lie Perturbation Theory. E. Rosengaus and R. L. Dewar.
1C2. ICRF Oscillations of an Inhomogeneous Plasma Cylinder. T. E. Cayton and H. R. Lewis.
1C3. Kinetic Effects on Ballooning Mode Beta Criteria in Tokamaks. G. Rewoldt, W. M. Tang, and M. S. Chance.
1C4. Numerical Studies of MHD Modes with Singular Behavior. J. Manickam, R. C. Grimm, R. L. Dewar, M. S. Chance, and A. E. Miller.
1C5 Electrostatic Effects on Variational Principles for Anisotropic Plasmas. T. M. Antonsen, Jr. and Y. C. Lee.
1C6. Does Ballooning Mode Limit the Tokamak Beta?. T. Tuda, M. Azumi, and G. Kurita.
1C7. Kinetic Study of Ballooning Mode. T. Tuda, K. Itoh, S. I. Itoh, and S. Tokuda.
1C8. The Influence of Diffraction on Ergodic Waves. E. Ott and T. M. Antonsen, Jr..
1C9. Trapping in Thermal Barriers. X. Z. Li and G. A. Emmert.
1C10 Computer Simulation Studies of the Effect of Hot Electrons on the MHD Flute Instability. R. Bharuthram, A. T. Lin, and J. M. Dawson.
1C11. Orbit-Averaged and Implicit Particle Codes. R. P. Freis, B. I. Cohen, J. A. Byers, and V. A. Thomas.
1C12. Electromagnetic Drift Modes Driven by Ion Pressure Gradients in Tokamak. D-I. Choi and W. Horton.
1C13 Destruction of Adiabatic Invariance. D. H. Dubin and J. A. Krommes.
1C14 Numerical Simulation of Burning Plasmas in Compact Toroids. R. N. Byrne and W. Grossmann.
1C15 Model of Anomalous Resistivity in Two-Dimensional MHD Calculation of Field-Reversed Theta Pinches. Z. A. Pietrzyk.
1C16. Microstable Sloshing Ion Mirror Plasma?. M. E. Rensink, D. E. Baldwin, and B. G. Logan.
1C17 Equilibrium of Diffuse Minimum-B Mirrors. D. A. D'Ippolito and J. P. Freidberg.
1C18 Absorption of Kink-Like Modes at the Alfven Resonance in Current Carrying Low-Beta Plasmas. K. Appert, B. Balet, R. Gruber, F. Troyon, T. Tsunematsu, and J. Vaclavik.
1C19. Ideal MHD Stability of the EBT Configuration. J. P. Freidberg.
1C20. VAX Computer Performance for Particle Simulation. J. S. Wagner and T. Tajima.
1C21. Field Line Geometry for Ergodic Magnetic Limiters. R. L. Miller, F. W. McClain, T. Ohkawa, and T. S. Wang.
1C22. High-n Kinetic Ballooning Modes in Tokamaks. C. Z. Cheng.
1C23. Two-Frequency Fermi Map. J. E. Howard, M. A. Lieberman, and A. J. Lichtenberg.
1C24. Invariant Probability Distribution on a Strange Attractor. A. B. Rechester and R. B. White.
1C25. Enhancement of Classical and Neo-Classical Diffusion by Narrow Band Turbulence. T. Ohkawa.
1C26. Computer Simulation of Non-Linear Ion-Electron Instability. R. H. Berman, D. J. Tetreault, T. H. Dupree, and T. Boutros-Ghali.

1C27. Stability Studies of Compact Toroids. W. Grossmann, E. Hameiri, and H. Weitzner.
1C28. Alpha Particle Loss and Energy Deposition in Tandem Mirrors. J. F. Santarius and J. D. Callen.
1C29. Numerical Studies of Toroidal Resistive Instabilities. R. G. Storer and R. C. Grimm.
1C30. Effect of Elongation on the Stability of Drift Waves. M. Rosenberg and R. E. Waltz.
1C31. Numerical Simulation of TMX Operation. J. M. Gilmore and G. E. Gryczkowski.
1C32. Anomalous Transport Effects on Electron Heating by a Finite Spectrum of Lower Hybrid Waves. M. G. McCoy and R. W. Harvey.
1C33. Theory of Ion Compton Scattering for Drift Wave Turbulence in a Sheared Magnetic Field. P. H. Diamond and M. N. Rosenbluth.
1C34. Effects of Nuclear elastic Scattering on Advanced Fuel Burns. J. Galambos, P. Stroud, J. Gilligan, E. Greenspan, and G. H. Miley.
1C35. Effect of Plasma Current on Restoring Force in Toroidal-Helical Configuration. T. Yamagishi.
1C36. Collisionless Reconnection With Parallel Electron Drift. B. Chike-Obi and B. Coppi.
1C37. The Rippling Mode. A. B. Hassam, J. F. Drake, and Y. C. Lee.
1C38. The Kinetic Theory of Ballooning Modes for Multipoles. M. W. Phillips, K. R. Symon, S. C. Prager, and J. D. Callen.
1C39. Numerical Investigation on Sawtooth Oscillations in Tokamak NBI Experiments. M. Okamoto, T. Amano, K. H. Shimizu, M. Azumi, S. Tokuda, S. Yamamoto, and Y. Shimomura.
1C40. Ion Cyclotron Resonances at High Energy in 2XIIB. M. Tagger.
1C41. Plasma Operation Contours for the FED. W. A. Houlberg.
1C42. Kinetic Effects on the Toroidal Ion Temperature Gradient Drift Mode. P. Terry, W. Anderson, and W. Horton.
1C43. Bifurcations of Periodic Orbits and of Chaotic Attractors in the Three Wave Problem. C. Bohanon and J-M. Wersinger.
1C44. Safety Factor Profile Optimization of High n Ideal Ballooning Mode Stability of Tokamaks. W. A. Cooper.
1C45. Computer Simulation of Generalized Adiabatic Reversed Field Mirror. S. Wollman and H. Grad.
1C46. Fokker-Planck simulation of the Sawtooth Neutron Production on PLT. Y. C. Sun and R. M. Kulsrud.
1C47. Disruption Control With Helical Coils. R. B. White, D. A. Monticello, W. Park, and H. Ikezi.
1C48. Pumping of Thermal Barriers in Tandem Mirrors by Induced Radial Transport. D. E. Baldwin.

Thursday, April 9

2A 8:30 AM ORAL SESSION
LBJ Auditorium
T. E. Cayton and K. Molvig, Chairmen

2A1. Neoclassical Transport Theory of Impurities in Tokamaks. S. P. Hirshman.
2A2. Steady State Tokamaks With the Toroidal Current Driven by the Synchrotron Radiation. J. M. Dawson and P. Kaw.
2A3. Comparison Between Calculations and Experimental Results from ZT-40 Discharges. J. P. Christiansen and R. A. Gerwin.
2A4. Kinetic Theory of Alfven Wave Heating. D. W. Ross, G. L. Chen, and S. M. Mahajan.

10:30-10:45 AM Coffee Break

2A5. Finite Beta Effects on the Nonlinear Evolution of the (m=1;n=1) Tearing Mode in Tokamaks. J. A. Holmes, B. A. Carreras, H. R. Hicks, and K. E. Rothe.
2A6. Transport Theory of a Rotating Plasma. S. K. Wong and K. H. Burrell.
2A7. Verification of the Classical Theory of Stellarator Transport. H. E. Mynick.

12:15-1:30 PM Lunch

2B 1:30-3:15 PM POSTER SESSION
(plus optional posters from Oral Session 2A)
Thompson Conference Center

2B1. Role of Beta Limits on Reactor Q Value in EBT. N. A. Uckan and D. A. Spong.
2B2. Particle-Confinement Criteria for Axisymmetric Field-Reversed Magnetic Configurations. M-Y. Hsiao and G. H. Miley.
2B3. Beam-Driven Currents and Heating in Tokamaks by Multi-MeV Particle Beams. D. R. Mikkelsen and M. A. Firestone.
2B4. Monte Carlo and Analytical Evaluations of Resonant Transport in MFTF-B. J. A. Byers, R. H. Cohen, and J. K. Nash.
2B5. Development of an Ion Cyclotron Heating Package of BALDUR. C. F. Karney, D. W. Hwang, and J. M. Hovey.
2B6. Low-m Ballooning Stability of an Axisymmetric Tandem Mirror. B. Hafizi and D. A. D'Ippolito.
2B7. Alfven Resonance Heating of a Theta-Pinch. R. Sanchez.
2B8. Microstability of the EBT Boundary. N. A. Krall and N. T. Gladd.
2B9. Transport Code Simulations of Lower Hybrid Heating in Alcator C, Using a Modified Electron Thermal Diffusion Coefficient. R. Englade, B. Coppi, and P. T. Bonoli.
2B10. Loss-Cone Effects on Relativistic Electron Rings in EBT. S. Hamasaki, N. A. Krall, and J. L. Sperling.
2B11. Magnetic Noise in an Igniting Plasma. F. Pegoraro.
2B12. Nonlinear Universal Modes with Diffusive Electrons. C. O. Beasley, Jr., K. Molvig, W. I. Van Rij, and J. C. Whitson.
2B13. Periodic Large-Amplitude MHD Activity in Beam-Heated Tokamaks. J. Hogan.
2B14. Hybrid Simulation of Ohkawa Currents. T. A. Brengle and B. I. Cohen.
2B15. Radial Transport in Tandems. J. R. Myra, P. J. Catto, and R. D. Hazeltine.
2B16. Tearing Mode Stability of a General Cross Section Tokamak. M. S. Chu, F. J. Helton, J. K. Lee, and T. H. Jensen.
2B17. Whistler Instability of the Thermal Barriers. C. Litwin and R. N. Sudan.
2B18. Effects of Poloidal Electric Field on EBT Transport. M. Mond and Y-P. Pao.
2B19 Derivation of Equations Describing Mode-Conversion and Tunneling Using a Variational Principle. R. J. Kashuba.
2B20. The Effect of Cusp and Mirror Coils on Field Line Reconnection in a Field Reversed Theta Pinch. R. D. Milroy and J. U. Brackbill.
2B21. Neoclassical Resistive q(psi)-Conserving-Tokamak Equilibria. D. B. Nelson and L. A. Charlton.
2B22. Magnetic Field Reconnection Rates. W. Park, D. A. Monticello, R. B. White, and J. B. Taylor.
2B23. Statistical Magnetohydrodynamics of a Reversed-Field Pinch. L. Turner.
2B24. Minimum Energy Toroidal Equilibria. A. Bhattacharjee and J. Wiley.
2B25. MHD Stability Near The Magnetic Axis of a Compact Toroid. K. Nguyen and T. Kammash.
2B26. The Effects of Parallel Currents on Tearing Modes. D. A. Hitchcock, S. M. Mahajan, R. D. Hazeltine, and G. Craddock.

2B27. A Variational Method for the Evolution of Toroidal Plasmas. G. Erlebacher.
2B28. Hamiltonian Field Formulation of Two-Dimensional Vortex Fluids, Guiding Center Plasmas and the One-Dimensional Vlasov-Poisson Equations. P. J. Morrison.
2B29. Magnetic Reconnection and Island Formation in Nonequilibrium Field Reversed Configurations: The Effect of Finite Thermal Conductivity. D. W. Hewett and C. E. Seyler.
2B30. Lower-Hybrid-Drift Instability in the EBT Boundary Layer. N. T. Gladd.
2B31. Nonlinear Steady-State Coupling of LH Waves by a Waveguide Array. K. Ko.
2B32. Electron Cyclotron Resonance Heating of MFTF-B at Relativistic Energies. B. H. Hui and K. R. Chu.
2B33. Relaxation of Magnetized Plasmas. K. Matsuda.
2B34. Nonlinear Coupling of Lower Hybrid Waves. K. Theilhaber.
2B35. Transport Study of ISX-B Flux-Conserving Tokamak Heating Scenarios. L. A. Charlton, R. A. Dory, D. J. Sigmar, and D. W. Swain.
2B36. Tokamak Currents Driven by a Pulsed Relativistic Electron Beam. D. A. Ehst.
2B37. Ion Thermal Conductivity for a Pure Tokamak Plasma. C. Bolton and A. A. Ware.
2B38. Anomalous Impurity Ion Transport Due to Magnetic Fluctuations. J. Y. Hsu, R. W. Harvey, and S. K. Wong.
2B39. Field Line Reconnection on a Hydromagnetic Time Scale. F. Brunel, T. Tajima, and J. M. Dawson.
2B40. Fluid Instability of Field-Reversed Theta Pinches. J. R. Cary.
2B41. Tearing Modes in Stellarator-Tokamaks. H. R. Hicks, B. A. Carreras, J. A. Holmes, and V. E. Lynch.
2B42. Zero-Dimensional Confinement Modelling of a Field-Reversed Configuration. L. C. Steinhauer.
2B43. Gyrokinetic Approach in Particle Simulation. W. W. Lee and W. M. Tang.
2B44. Shear Alfven Transport of Fast Alpha Particles. W. R. Sutton, C. K. Choi, and G. H. Miley.
2B45. Calculation of Non-Axisymmetric MHD Instabilities in Toroidal Plasmas with D-Cross Sections. A. I. Shestakov and J. Killeen.
2B46. A 3D Alternating dimension Equilibrium and Transport Code for EBT. W. H. Miner, N. K. Winsor, and H. Grad.
2B47. Ion Cyclotron Heating of an EBT Plasma. A. Fukuyama and T. Tajima.
2B48. Anisotropy-Driven Instabilities in Mirror Experiments. G. R. Smith and W. M. Nevins.

2C 3:30-5:15 PM POSTER SESSION
Thompson Conference Center

2C1. Collisional Drift Waves in the Spheromak Geometry. R. Marchand and P. N. Guzdar.
2C2. On the Fractal Dimension of Power Spectra. S. Johnston.
2C3. High Beta Taylor Equilibrium. A. Hasegawa.
2C4. A New Diagnostic for q(r) in Tokamaks: Alfven Wave Resonant Absorption. R. D. Bengtson, S. M. Mahajan, G. L. Chen, and D. W. Ross.
2C5. Plasma Heating Using Axisymmetric (1=0) Alfven Waves. G. L. Chen, S. M. Mahajan, and D. W. Ross.
2C6. Transport Modeling of Impurity Control by Direct Momentum and Inertial Effects. D. J. Sigmar and H. C. Howe.
2C7. Beta Limitations in Spheromak and RFM Configurations. H. E. Dalhed.
2C8. Collisionless EBT Transport and Poloidal Electric Field. Y-P. Pao.
2C9. Inhomogeneity Effects on ICRF Waves in EBT-S. J. L. Sperling.
2C10. Calculation of the Statistical Properties of Turbulent Dynamical Systems. R. V. Jensen and C. R. Oberman.
2C11. On the Existence of Slit and Very Rectangular Equilibria in Reversed Field Theta Pinches. D. V. Anderson and J. H. Hammer.
2C12. Low Frequency Electromagnetic Trapped Particle Modes in a Toroidal Plasma. B. Lane and T. M. Antonsen, Jr..
2C13. Quasilinear Theory of ICRF Current Drive. S. C. Chiu, V. S. Chan, J. Y. Hsu, G. E. Guest, R. Prater, and J. Rawls.

2C14. The Effect of Bundle Divertors on Magnetic Islands in Tokamaks. G. Bateman and R. N. Morris.
2C15. Ion Cyclotron Resonance Heating and Its Effect on Confinement in Tokamaks. K. W. Whang, G. J. Morales, and B. D. Fried.
2C16. Computer Simulation of Lower-Hybrid Heating in Tokamaks. J. M. Ogden, S. Bernabei, and C. Singer.
2C17. Anomalous Transport in a Tokamak with Large Flow Velocity. C. S. Chang.
2C18. Fast Moment Equation Method for Solving the Grad-Shafranov Equation. H. K. Meier.
2C19. Numerical simulation of Transport in Tokamaks with Ripple. A. Bayliss, H. Grad, and O. Betancourt.
2C20. Singularity (Catastophe) Theory and Ideal MHD. D. J. Elkin and S. Johnston.
2C21. Pressure Profile Effects on Ballooning Mode Stability. D. J. Strickler, Y-M. Peng, and D. K. Lee.
2C22. Eddy Currents in Conducting Shells Due to Plasma Motion. M. S. Chance, R. C. Grimm, S. C. Jardin, and J. Manickam.
2C23. The Effects of Small Amplitude MHD Instabilities on Magnetic Field Topology. N. J. O'Neill, A. I. Shestakov, and A. A. Mirin.
2C24. Non-Resonant and Higher Order RF Current Drive. P. K. Kaw.
2C25. Inference of Magnetic field Profiles in the Reversed Field Pinch. R. A. Gerwin, R. A. Nebel, and D. W. Hewett.
2C26. Saturation and Transport by the Lower Hybrid Drift Instability in Two Dimensions. J. F. Drake and J. D. Huba.
2C27. Particle Losses in Reversed Field Devices Due to Loss-Cone-Like Scattering. Q. T. Fang and G. H. Miley.
2C28. Nonlinear Threshold of Toroidal Field for the Collisionless Tearing Instability. T. Tajima.
2C29. Finite n Ballooning Modes with ERATO. R. Gruber, F. Troyon, T. Tsunematsu, and K. Appert.
2C30. Fusion Efficiency of a DD Tandem Mirror Reactor. A. A. Mirin, G. P. Tomaschke, B. G. Logan, and M. E. Rensink.
2C31. Low Frequency Electrostatic Drift Waves in a Plasma Sheath. Y. C. Lee, R. Marchand, and N. T. Gladd.
2C32. Simulation Study of the Current-Driven Electrostatic Ion Cyclotron Instability. P. L. Pritchett, M. Ashour-Abdalla, and J. M. Dawson.
2C33. Eddy Currents in Conducting Shells Due to Plasma Motion. M. S. Chance, R. C. Grimm, S. C. Jardin, and J. Manickam.
2C34. ICRF Heating by Ion Orbit Parametric Resonance. A. K. Ram, V. B. Krapchev, and A. Bers.
2C35. Current Drive Schemes for Tokamak Reactors. D. K. Bhadra and C. Chu.
2C36. Coil Optimization for Ergodic Magnetic Limiters. T. S. Wang, F. W. McClain, R. L. Miller, and T. Ohkawa.
2C37. Stochastic Damping of an Obliquely Propagating Wave. C. R. Menyuk, J. M. Dawson, V. K. Decyk, B. D. Fried, and G. J. Morales.
2C38. Ideal and Resistive MHD Stable Startup for the Reversed-Field Pinch Reactor. R. A. Nebel, R. W. Moses, D. W. Hewett, and G. H. Miley.
2C39. Scaling of the Electron Energy Confinement Time. N. Sharky and B. Coppi.
2C40. A Steady-State Spheromak Maintained by Coalescence. A. Reiman.
2C41 Magnetic Spectra of current Carrying Media. C. Chu and J. Y. Hsu.
2C42. Theory of Non-Linear Ion-Electron Instability. T. Boutros-Ghali and T. H. Dupree.
2C43. Finite-n Ballooning Mode Theory for Axially Symmetric Toroidal Plasmas. D. Dobrott and R. W. Moore.
2C44. Kinetic Theory of Driven Reconnection at an X Point. R. W. Moses and D. W. Hewett.
2C45. Neoclassical Ripple Transport in the Low Collisionality Regime. J. D. Callen and K. C. Shaing.
2C46. Self-Consistency and Space-Charge Effects in Intense-Beam Free-Electron Lasers. A. Auslender, G. Erlebacher, and S. Johnston.
2C47. Lagrangian Formulation of Neoclassical Transport Theory. I. B. Bernstein and K. Molvig.
2C48. Collisionless Tearing and Twisting Modes in the Presence of Trapped Particle Drifts. S. M. Mahajan, R. D. Hazeltine, and D. A. Hitchcock.

Friday, April 10

3A 8:30 AM ORAL SESSION
LBJ Auditorium
D. R. Dobrott and R. Grimm, Chairmen

3A1. Three-Dimensional Analysis of Ballooning Modes in Tandem Mirrors. W. M. Nevins, D. E. Baldwin, T. B. Kaiser, and L. D. Pearlstein.
3A2. Renormalized Tearing Mode Turbulence and the Major Disruption. R. D. Hazeltine, P. H. Diamond, and B. A. Carreras.
3A3. The Ambipolar Electric Field in Stochastic B-Field Models. R. W. Harvey, J. Y. Hsu, and M. G. McCoy.
3A4. Near-Term Feasibility of Advanced Fuel Fusion Reactors. B. Coppi.

10:30-10:45 AM Coffee Break

3A5. A Monte Carlo Formalism for Studying the Banana-Kinetic Equation in Toroidal Systems With Field Ripple. R. J. Goldston, R. B. White, and A. H. Boozer.
3A6. Theoretical View of a High Beta Toroidal Plasma Experiment. S. C. Prager, A. G. Kellman, M. W. Phillips, E. J. Strait, and M. C. Zarnstorff.
3A7. Relaxation Toward States of Minimum Energy in a Compact Torus. S. Riyopoulos, A. Bondeson, and D. Montgomery.

12:15-1:30 PM Lunch

3B 1:30-3:15 PM POSTER SESSION
(plus optional posters from Oral Session 3A)
Thompson Conference Center

3B1. Tilt and Shift Mode Stability in Spheromaks with Line Tying. J. M. Finn and A. Reiman.
3B2. Lower Hybrid Wave Ray Tracing for Spheromak Heating. J-M. Wersinger, B. Hui, E. Ott, and P. T. Bonoli.
3B3. Beta Critical in the Second Region of Stability. D. A. Monticello, H. R. Strauss, J. Manickam, W. Park, R. C. Grimm, S. C. Jardin, R. B. White, and R. L. Dewar.
3B4. Field Error Studies in Modular Stellarators. D. T. Anderson.
3B5. Scalar and Tensor Pressure Distribution for Axisymmetric MHD Analysis of Barrier Tandem Mirrors. N. S. Kim, R. W. Conn, and G. W. Shuy.
3B6. Analysis of Heating and Thermal Stability Near Ignition. V. Fuchs, M. M. Shoucri, L. Harten, and A. Bers.
3B7. Long Wavelength Collisional Tearing Modes in a Stochastic Magnetic Field. R. G. Kleva.
3B8. Energy Multiplication in Tokamaks with Enhanced Radial Electric Fields. W. B. Downum, G. H. Miley, and C. K. Choi.
3B9. Linear Theta Pinch Reactor With Pulsed Mirror End Plug. A. K. Sen.
3B10. Energy Principle Code for MHD Tearing Modes in a General Cross Section Plasma. J. K. Lee, M. S. Chu, and T. H. Jensen.
3B11. Analytical Modeling of Sawtooth Oscillations in Tokamaks. K. Yamazaki, K. McGuire, M. Okabayashi, and G. L. Schmidt.

3B12. RF Plugging Near the Ion cyclotron Frequency. B. M. Lamb, G. Dimonte, and G. J. Morales.
3B13. MHD Stable Equilibria of an Ion Ring Confined Plasma. L. Sparks, A. Mankofsky, R. N. Sudan, J. M. Finn, and J. Denavit.
3B14. Stability Study of the Expanded Spheromak. L. C. Bernard, F. J. Helton, F. W. McClain, and H. E. Dalhed.
3B15. Unstable Entropy Mode in a Current Carrying Turbulent Plasma and Double Layer Formation. C. S. Liu, Y. C. Lee, and V. K. Tripathi.
3B16. Hamiltonian Formulation of the Gyrokinetic Equation. H. V. Wong.
3B17. Alfven Wave Heating of Toroidal Plasmas. C. Kieras, J. A. Tataronis, and A. Salat.
3B18. Internal Modes and Termination of Quiescence for the Reversed-Field Pinch. D. D. Schnack and R. A. Nebel.
3B19. Monte Carlo Modeling of He Enrichment and Plenum Neutral Conditions in Divertor Devices. D. Heifetz, M. Petravic, and D. Post.
3B20. Low Frequency Heating of Doublet. M. Kress and H. Grad.
3B21. A Theory of Hot Electron Plasmas. Y. Matsuda, W. M. Nevins, and R. H. Cohen.
3B22. Kinetic Ballooning-Interchange Modes in Tandem Mirrors. X. S. Lee and P. J. Catto.
3B23. A Generalized Model of Field-Reversed Equilibria Created by Monoenergetic Ions. J. E. Brandenburg and R. F. Post.
3B24. Coupling of Hot Electron Interchange and Ion Bernstein Modes in EBT. K. T. Tsang and C. Z. Cheng.
3B25. Space-Resolved Cyclotron Radiation as a Potential Field Profile Diagnostic. W. B. Riesenfeld.
3B26. Sensitivity of Equilibrium to Coil Configuration in Tandem Mirrors. T. B. Kaiser, D. E. Baldwin, J. A. Byers, and L. D. Pearlstein.
3B27. Stochastic Heating of Ions by an Ion-Cyclotron Wave in an Inhomogeneous Magnetic Field. K. Nozaki, B. D. Fried, A. Fukuyama, and G. J. Morales.
3B28. Ion Thermal Conduction in Compact Toroids. S. P. Auerbach.
3B29. Minimum Number of Modes for the Approximation of the Solutions of the Navier-Stokes Equation. Y. M. Treve.
3B30. Parameter Survey of MFTF-B. R. A. Jong and R. S. Devoto.
3B31. Electron Thermal and Warm Plasma Effects on Ion-Cyclotron Microinstabilities in Mirror Devices. T. D. Rognlien.
3B32. Analysis of the Density Profiles in Various Experiments. N. Sharky and B. Coppi.
3B33. Radial Eigenmode Stability for "Bumpiless" EBT. J. W. Van Dam, H. L. Berk, M. N. Rosenbluth, and D. A. Spong.
3B34. MHD Stability of the Spheromak Configuration. S. C. Jardin, M. S Chance, R. L. Dewar, R. C. Grimm, D. A. Monticello, and W. Park.
3B35. Classical Diffusion and Transport in Torus II. H. C. Lui.
3B36. Banana Drift Transport in Tokamaks with Ripple. R. Linsker and A. H. Boozer.
3B37. Interactions of Streaming Particles and Electromagnetic Ion cyclotron Instability. L. P. Mai.
3B38. Globally Reconnecting Tearing Modes in the Reversed-Field Pinch. E. J. Caramana and D. D. Schnack.
3B39. Numerical Simulation of the Beta II Experiment. D. E. Shumaker, J. K. Boyd, S. P. Auerbach, and B. McNamara.
3B40. Effects of Local Current Gradients on Magnetic Reconnection. G. Bertin.
3B41. Monte Carlo Simulation of Ion Transport in Analytical Tokamak and Stellarator Fields. W. Lotz and J. Nuhrenberg.
3B42. Simulations of Ion Cyclotron Resonance Heating in Tokamaks. J. N. Leboeuf, K. W. Whang, T. Tajima, and M. Makino.
3B43. Self-Adjointness of the Vlasov-Maxwell Equation. E. Maschke, R. R. Dominguez, and H. L. Berk.
3B44. Alfven Wave Cyclotron Resonance Heating. S. Yoshikawa, R. B. White, and C. R. Oberman.
3B45. Magnetohydrodynamic Stability of Low-Beta Helically Symmetric Straight Equilibria. M. Mond and H. Weitzner.
3B46. Stellarator Equilibria at Finite Aspect Ratio. D. Lortz and J. Nuhrenberg.
3B47. Ballooning Modes in Low-Beta Stellarators. D. Lortz and J. Nuhrenberg.
3B48. Omnigenous Stellarators. D. Lortz and J. Nuhrenberg.

EBT STABILITY THEORY

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Stability of EBT for curvature driven modes requires important modifications from standard MHD techniques, as the hot electron component has drift frequencies larger than the usual MHD frequency. In addition oscillations of interest can take place at frequencies comparable to the ion cyclotron frequency. We have developed a kinetic MHD method that takes these special characteristics of an EBT plasma into account. We are currently treating a high m-number trapped particle formalism to describe axial effects, and an exact z-pinch model to treat the radial aspects of the problem. It has been shown that when diamagnetic drifts reverse the curvature drifts, the usual interchange instability is stabilized, but the system is susceptible to a magnetic instability similar in character to a mirror mode. We find that stable operation of EBT plasmas is generally achieved if the ion density is neither too large nor too small. At low density the conventional hot electron interchange is excited and at high density the mirror-like mode. However, we find islands of parameter space where instability is possible even in the generally stable window. As long as the background beta is low, the stability window is compatible with scaling to a larger size and higher field EBT.

The Lee-Van Dam threshold, arising from increasing the background plasma beta still persists. The mode is insensitive to ion Larmor radius effects, and the background β threshold decreases due to moderate electron Larmor radius effects. Only with sufficiently large electron Larmor radius effects is the Lee-Van Dam threshold for the interchange mode avoided.

This work is supported by DOE Grant DE-FG05-80ET 53088.

The Motion of a Charged Particle in a Magnetic Field with Nearly Helical Symmetry

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and

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The behavior of a charged particle in a given static magnetic field is analyzed in terms of the Hamiltonian of the moving particle and the technique of repeated canonical transformations to identify possible adiabatic invariants and drift motions. This method, which was first introduced by Gardner[1] for general fields and later extended by Weitzner[2] to nearly axisymmetric fields, provides an elegant way of analyzing particle motion when the given magnetic field is characterized by small components which scale as some power of the particle gyroradius ε. With the goal of providing a better understanding of the complex particle motion in stellarator and torsatron plasma configurations, we consider a helically symmetric magnetic field which is perturbed by a nonsymmetrical component. The nonsymmetrical field could arise, for example, from curvature effects. The method of repeated canonical transformations reveals the existence of adiabatic invariants, depending on the strength of the perturbing field, the strength of the poloidal component of the helical field, and the magnitude of the helical period. Typically, a first adiabatic invariant is the magnetic moment. A second adiabatic invariant may or may not exist, depending on the strengths of the various components of the magnetic field. The nonexistence of a second adiabatic invariant has strong implications on the long time drift motion of the particle. Comparisons with numerical solutions of the equations of motion will be made.

1. C. S. Gardner, Phys. Rev. 115, 791 (1959).
2. H. Weitzner, NYU, Courant Inst. of Math. Sciences Report MF-97, November 1980.

Plasma Properties in Poloidal Divertors*

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and G. Petravic

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ABSTRACT

A computational model has been constructed for studying plasma flow and neutral transport in divertors, and in the vicinity of (pumped) limiters. Plasma flow is modeled by fluid equations, while Monte Carlo methods are used for neutral gas transport. The two treatments are combined into a single model capable of producing self-consistent solutions in a variety of physical situations corresponding to most of the existing and planned tokamaks including PDX, DOUBLET, INTOR, and FED. While quite general geometries can be accommodated by the code, its early use has been in understanding general behavior of plasmas in rectangular divertor channels. Plasma flow has been studied for input fluxes (into divertor) ranging from 10^{17} to 10^{18} ions/cm^{2}sec, and energy fluxes corresponding to 100-2000 eV per electron-ion pair. For narrow, well-pumped channels, flow velocities are around 10^6 cm/sec, and plasma densities 10^{11} to 10^{12}/cm^3 throughout the channel. Neutrals emitted at the plate easily escape through divertor throat. There is some ionization of cold neutrals close to the plate resulting in a plate ion flux exceeding the input flux by a factor of up to 3. Much more interesting and important is the high density operation achieved by increasing the neutral gas density at the plate. This occurs with a low pump conductance, wide plasma flows, and higher particle fluxes. Most of the neutrals are now ionized resulting in plate to input ion flux ratios of 20 or more, and the electron temperature lowered by the same factor. In this way, plasma is cooled to approximately 10 eV where recombination becomes important and gaseous divertor mode of operation begins. This has a dramatic (positive) effect on sputtering yield and the impurity problem. However, plasma velocity in the channel is well below its maximum at the plate, given by $v_{plate} = (5/3\ T_i/m_i + T_e/m_i)^{1/2}$. Plasma density at the throat is, therefore typically above 10^{13}/cm^3 and could exceed 10^{14}/cm^3. The credibility of the high density mode of operation depends partly on the cross-field diffusion rates in the whole of the scrapeoff region. Since diffusion coefficients are not known or understood, only qualitative conclusions can be reached on this point. Diffusion coefficients proportional to temperature appear to be more favorable in this respect. Though not carried out under optimum conditions, experiments on DOUBLET III[(1)], ALCATOR[(2)], and PDX[(3)] show a large amount of recycling and dramatic increase in neutral pressure in the vicinity of collecter plate, consistent with our predictions.

*Work Supported by the U.S. DoE Contract No. DE-AC02-76-CHO3073.

(1) A. Kitsuneazaki et al., A Single Hull Poloidal Divertor Experiment in DOUBLET III.
Bull. Am. Phys. Soc. 8, Vol. 25 (October 1980).

(2) D. O. Overskei, Efficacy of Passive Limiter Pumping of Neutral Particles Phys. Rev. Lett. 3, Vol. 46 (January 1981)

(3) R. Jacobsen, private communication

SIMULATION OF ISLANDS IN TOKAMAKS

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Global perturbations of Tokamak equilibria in three dimensions are under investivation by means of a computer code that is based on the classical variational principle of ideal magnetohydrodynamics. Although a nested family of toroidal flux surfaces occurs in the numerical method, it is possible to model smaller islands successfully. The presence of islands can be detected by tracing magnetic lines or by examining properties of the current density or by estimating the Jacobian of a transformation to flux coordinates. Bifurcated equilibria associated with unstable internal modes are found to have significant islands. But deformations of the surface of the plasma such as might be introduced by a bundle divertor do not seem to generate big islands. Similarity solutions of the equilibrium equations are calculated exhibiting large helical distortions that are free of islands.

BREAKDOWN OF ONSAGER SYMMETRY IN NEOCLASSICAL TRANSPORT THEORY

K. Molvig, Massachusetts Institute of Technology and The Institute for Fusion Studies
and
L.M. Lidsky and K. Hizinidis, Massachusetts Institute of Technology
and
I.B. Bernstein, Yale University
and
K. Swartz, Institute for Fusion Studies

The effect of electron turbulence on the neoclassical pinch effect and the bootstrap current is considered. We argue that known turbulence levels will destroy (or greatly diminish) the bootstrap current and some of the fluxes contributing to the pinch effect. The Ware effect remains, however, and the symmetry between overall fluxes is then broken. A recently developed Lagrangian[1] formulation of neoclassical theory is utilized. The theory naturally separates the collisionless flows, like the Ware effect on trapped particles, from fluxes due to collisional scattering and leads to a picture in which the pinch and bootstrap effects can be understood as microscopic inverse processes and thus clearly, conjugate (although unrelated to the Ware effect). Furthermore, the underlying effects are confined to a very narrow layer of circulating particles near the trapped particle boundary that are sensitive to collisional scattering. Turbulence mixes the idealized trajectories which are scattered by collisions. Instead of well-defined but very sensitive trajectories, one has wide, probabalistic blurs, whose mean properties are not so sensitive to collisional scattering. This eliminates the boundary layer contributions to the neoclassical fluxes and breaks the symmetry.

[1]I.B. Bernstein and K. Molvig, Sherwood Meeting 1981.

This work is supported by DOE Grant No. DE-FG05-80ET 53088.

A SURVEY OF FLUCTUATION MEASUREMENTS IN TOKAMAKS AND COMPARISON WITH VARIOUS THEORIES OF ANOMALOUS ELECTRON TRANSPORT

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Many theories have been developed which invoke turbulence to explain the anomalously large electron thermal conduction in tokamaks. Now, low frequency ($\omega << \omega_{ci}$) electrostatic and magnetic fluctuations have been measured in several tokamaks. Here we summarize the experimental results and compare them with predictions of various theories of turbulence and transport on tokamaks.

The experimental measurements are all consistent with the assumption of strong turbulence. Density fluctuation measurements in PLT; ATC,[1,2] Alcator-A[2] and Microtor all show a broad frequency spectrum for each k as opposed to one or two dominant frequencies for each k as one expects from normal modes. Also, all show that the turbulence is isotropic in the plane perpendicular to B, $\bar{k}_r \approx \bar{k}_\theta << k_\parallel$. Broadband magnetic fluctuations $\tilde{B}_r(\omega)$ and $\tilde{B}_\theta(\omega)$ have now been measured in the Macrotor[4] and Caltech[5] tokamaks. Both show $\tilde{B}_r \simeq \tilde{B}_\theta \sim 10^{-4} B_r$. The spectra show no reproducible or coherent structures except for the low-m MHD modes.

No single theory explains both the observed spectra and energy confinement time. Using the measured level of magnetic fluctuations in the Macrotor and Caltech tokamaks, the stochastic magnetic field transport model does not predict enough diffusion to account for the observed confinement times in these two experiments. Two theories, a renormalized drift turbulence theory[7] and a microtearing mode theory[8] give good agreement with the experiments on energy confinement times, but do not agree with the fluctuation spectra measured in the tokamaks. Other nonlinear theories including quasilinear theory[9] will also be discussed.

[1]E. Mazzucato, *Phys. Fluids* 21 (1978) 1063.
[2]C.M. Surko and R. Slusher, *Phys. Rev. Lett.* 37 (1976) 1747; *Phys. Rev. Lett.* 40 (1978) 400 and *Phys. Fluids* 23 (1980) 2425.
[3]Semet, Mase, Peebles, Luhmann and Zweben, *Phys. Rev. Lett.* 45 (1980) 445.
[4]S.J. Zweben, R. Taylor and C. Menyuk, *Phys. Rev. Lett.* 42 (1979) 1270.
[5]M.H. Hedemann and and R.W. Gould, *Bull. Am. Phys. Soc.* 25 (1980) 975.
[6]A. Rechester and M.N. Rosenbluth, *Phys. Rev. Lett.* 40 (1978) 38.
[7]K.Molvig, S.P. Hirshman, and J.C. Whitson, *Phys. Rev. Lett.* 43 (1979) 582.
[8]J.F. Drake, N.T. Gladd, E.S. Lin and C. Chang, *Phys. Rev. Lett.* 44 (1980) 994.
[9]W. Horton and R. Estes, *Nucl. Fusion* 19 (1979) 203.

Prospects for Fusion Plasma Theory

David B. Nelson
U.S. Department of Energy

Recent experimental advances have increased confidence in the scientific feasibility of fusion and have led to rising emphasis on reactor grade plasmas and on technological problems. At the same time, severe budgetary constraints have necessitated scrutiny to ensure the effectiveness of the various components of the fusion program. Under these circumstances, the future health of fusion plasma theory depends on its relevance and its cost-effective contribution to the overall research. However, one must avoid simplistic definitions of relevance and not equate it with near-term relevance. Some of the most pressing theoretical problems are extremely difficult and may require years of concerted effort for their solution.

Several recent studies have identified critical issues in the various confinement approaches which appear amenable to theoretical study. These will be reviewed and suggestions given for possible methods of attack. Historically, fusion plasma theory has served three roles: to elucidate physical principles leading to improved reactor concepts or better plasma properties, to aid in design of new experiments by predicting achievable parameters, and to interpret experimental measurements. In the past, limitations in both theoretical and experimental techniques led to concentration on the first role. Maturation of plasma physics now allows greater confrontation between theory and experiment and stronger emphasis on the second and third roles. As an applied research program, fusion plasma theory must aim at ultimate connection with experiment and reactor design. It must demonstrate that it can affect the pace, cost and risk of the overall fusion program. Examples will be given of theoretical investigations which appear to meet these goals. Criteria will be presented which may help in selecting research topics, and which may be useful in judging the worth of completed or ongoing research.

Guiding Center Orbits in Stellarators*

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A guiding center code has been employed to analyze single charged particle orbits in a modular stellarator for vacuum magnetic fields ($\nabla \times \vec{B} = 0$). The guiding center code utilizes a routine which constructs the filamentary coils from straight segments.

The orbits have been classified as being toroidally trapped, helically and/or modularly trapped, transitional, or circulating. Utilizing these orbit projections, the characteristics of various machines are described. Results are presented for orbits in IMS (Interchangeable Module Stellarator) and Proto-Cleo Stellarator.

* Work supported by U.S. D.O.E. under Contract No. DE-AS02-78ET53082 and NSF under Grant ECS-79-25418.

POSTER SESSION

NEUTRAL BEAM EFFECT ON BALLOONING MODE STABILITY*

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ABSTRACT

Recent experimental results from ISX-B suggest that beta limits for the onset of the ballooning instability are substantially above those predicted by MHD analyses. We propose an explanation of this result based upon a simple model for the effect of neutral beam pressure on ballooning mode stability. Specifically, our analysis shows that the stability limit on plasma beta remains relatively constant (or even increases) as beam pressure is added. Therefore, the stable total beta (plasma beta plus beam beta) is raised significantly by the presence of the beam. Saturation of β with increasing beam power will also be addressed.

*Work supported by the Department of Energy, Contract DE-AT03-76ET51011.

THE RADIAL EBT STABILITY PROBLEM*

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and

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ABSTRACT

The local theory of electromagnetic modes excited by hot electrons predicts that the stability of an EBT device requires the density ratio of the ring to core electrons to fall in a certain range determined by the operating parameters.[1] In this work we formulate the radial problem which allows us to deal with realistic profiles and then use a shooting method to obtain the stability regimes. We assume that both the hot electron interchange and the compressional Alfvén modes can be localized to the outside of the ring. This is consistent with the local solution in the high mode number limit and allows us to treat the low m case. The mode structure, stability thresholds and comparison with the experimental results will be presented.

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

[1]A. M. El Nadi (to be published).

POSTER SESSION REQUESTED

NUMERICAL STUDY OF TORUS II

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Single-fluid resistive magnetohydrodynamic equations are solved numerically in one- and two-dimensions to simulate both the initial implosion dynamics[1] and long-time-scale plasma evolution of the Torus II experiment. During the implosion phase, the equations are driven by prescribed boundary conditions for the poloidal and toroidal flux functions. Profiles of currents, magnetic fields, density, temperature, plasma beta, and safety factor q have been obtained. The plasma initially shifts radially outward while elongating axially; it then reverses, and its inward radial shift and axial contraction are coupled with loss of both plasma and current. The plasma equilibrated well radially, but not yet axially, so that $p = p(\psi)$ is not yet obtained, in contrast to circular cross-section screw pinches. Using implosion results as initial conditions, a one-dimensional MHD diffusion code, complete with resistivity, thermal conductivity, and radiation losses, is used to study the high-beta phase of the device. Maximum allowable impurity levels for successful operation are identified. The long-time-scale plasma motion is seen to vary axially, depending on initial conditions and impurity levels, while an outward radial shift is always present. Confinement times of 15 to 40 μsec. have been calculated.

Work supported by US Dept. of Energy.

1 H. C. Lui, C. K. Chu, Phys. Fluids 19, 1947 (1976).

2 R. Izzo, C. K. Chu, APS Bull. 25, No. 8, paper 5D8, October 1980.

BOUNDARY LAYER CORRECTIONS ON NEOCLASSICAL RIPPLE TRANSPORT IN TOKAMAKS*

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The discrete nature of the toroidal magnetic field coils spoils the symmetry of the tokamak and creates small modulations on the toroidal field called ripples. Particles trapped in the ripple well drift off the flux surface and enhance both particle and heat fluxes. In the usual ripple transport calculations,(1) the derivative of the perturbed particle distribution function in the velocity space is discontinuous at the boundary between ripple trapped and untrapped regions. To smooth out the particle distribution across the boundary, the particle distribution in the boundary layer is calculated by using the Wiener-Hopf technique. The correction to the ripple-trapped particle distribution away from the boundary layer and the ripple transport associated with it are obtained. We find that the particle diffusion and heat conduction coefficients are increased by about a factor of 2 and scale like $\nu^{-1/2}$ as $(\nu_{eff}/\omega_{b\delta})^{1/2} \rightarrow 1$. Even at $\nu_{eff}/\omega_{b\delta} = 10^{-2}$, the corrections are still non-negligible and are about 15%.

(1) J.W. Connor and R.J. Hastie, Nucl. Fusion, 13, 221 (1973).

* Work supported by the U.S. DOE under contract DE-AC02-80ER53104.

AMBIPOLARITY OF PARTICLE FLOW DUE TO MAGNETIC FLUCTUATIONS AND CHARGE FILAMENTATION INSTABILITIES*

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ABSTRACT

Using the quasilinear kinetic theory of transport in slab geometry we show that, contrary to the conventional description (e.g., Refs. 1 and 2), the particle flow from magnetic fluctuations due to local normal modes is independent of any global radial electric field and is automatically ambipolar on local spacial average over the radial extent of the modes. This follows essentially from local frame invariance in the direction perpendicular to the steady magnetic field or explicitly from the requirement that the locally-bounded magnetic fluctuations satisfy Ampere's law. Unlike the conventional description, this new result appears to be consistent with tokamak experimental data[3] on the plasma potential and rotation. Local deviations from ambipolarity, however, cause both inward and outward radial electric currents to flow. Despite cancellation from the overlapping of modes on adjacent singular surfaces, the currents produce local radial elecric fields and charge filaments with radial gradient length scales comparable to the spacing between singular surfaces. The filamentation process saturates when balanced against classical shear viscosity. The charge filaments and their corresponding shear in the local transverse E × B velocity can cause drift and shear-Alfvên modes to be Kelvin-Helmholtz unstable. These effects are illustrated with numerical solutions of the drift-Alfvên mode equations.

1. Rechester, A. B. and Rosenbluth, M. N., Phys. Rev. Lett. 40 (1978) 38.
2. Callen, J. D., Phys. Rev. Lett. 39 (1977) 1540.
3. Bell, M. G., Nucl. Fusion 19 (1979) 33.

*Work supported by the Department of Energy, Contract DE-AT03-76ET51011.

The Influence of Finite Gyroradius and Resistivity on the Alfven Wave Continuum*

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It is well known that in ideal MHD there is a continuous spectrum of real frequencies associated with shear Alfven waves which are singular on the surface $\omega = k_{\parallel} v_A$. The introduction of first-order gyroradius effects eliminates the singularities and hence the continuous spectrum and produces instead a discrete spectrum[1] of real frequencies related to the gyroradius. In the present work we examine the influence of the full gyroradius response on the Alfven spectrum using Fourier analysis in which singular modes are recognized by their behavior at infinity. If only the first-order gyroradius effect is retained, we recover the previous result that the singular continuum of MHD is indeed removed and replaced by a discrete spectrum of real frequencies. However, when the full gyroradius effects are included, this discrete real spectrum disappears and a continuum of singular modes reappears! The effect of resistivity on these new singular modes and on the original singular MHD modes will be discussed.

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*This work was supported by the United States Department of Energy Contract No. DE-AC02-76-CH03073.

†Also at Institute for Advanced Study, Princeton, New Jersey.

[1]M. N. Rosenbluth and P. H. Rutherford, Phys. Rev. Lett 34, 1428 (1975).

POSTER SESSION

NUMERICAL COMPUTATION OF RESISTIVE INSTABILITIES IN A TORUS

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A new numerical method for computing eigenfunctions and eigenvalues inside the singular layer of resistive MHD instabilities will be presented. It is motivated by several considerations. Existing analytical methods, such as the constant-ψ approximation and related procedures, become very inaccurate when applied to high β configurations such as the reversed field pinch, spheromak, and advanced tokamaks. Furthermore, such methods cannot readily be extended to include additional physical effects such as viscosity, which become important at high temperatures. Finally, a procedure is needed which is fast, accurate, automatic, and reliable, because it must be iterated many times for each singular layer, each growth rate, and each value of the magnetic Reynold's number $S \equiv \tau_R/\tau_A$. The new method is based on numerical integration of the Fourier transforms of the equations of Glasser, Greene, and Johnson.[1] Comparison to the analytical results of that paper shows reasonable qualitative agreement with its conclusions, but substantial quantitative discrepancy. Comparison to the computations of Freidberg and Hewett[2] on resistive instabilities in a cylindrical reversed field pinch shows reasonable agreement at moderate values of S. It shows that their method loses resolution for $S \gtrsim 10^4$ while the asymptotic matching method becomes inaccurate for $S \lesssim 10^4$, and it suggests interpretations of their observations. Finally, a scheme is presented for matching this inner region analysis to a corresponding computation of the ideal outer region eigenfunctions in a torus, such as that currently under development at Princeton.[3]

1. Glasser, Greene, and Johnson, Phys. Fluids 18, 875 (1975).
2. Freidberg and Hewett, LASL Report LA-UR 80-330, 6/30/80.
3. Grimm, Dewar, Manickam, and Chance, Bull. Am. Phys. Soc. 25, 8, 864 (1980).

PLASMA HEATING FROM UPPER HYBRID MODE CONVERSION IN AN INHOMOGENEOUS MAGNETIC FIELD*

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Large amplitude short wavelength electrostatic fields can be achieved at the upper hybrid resonance due to mode conversion process. As a consequence, a host of nonlinear and kinetic phenomena can take place. Among them, we have observed in our computer simulations the following: the generation of energetic electrons due to breaking of adiabatic electron motion in the wave field, the enhancement of electron second harmonic cyclotron heating at the double resonance ($\omega_{LH} = 2\omega_{ce}$), and the parametric instability in which the upper hybrid mode decays into another upper hybrid mode and a low frequency mode. The parametric instability is observed to enable the electrostatic upper hybrid wave to penetrate through its original cut-off to a distance proportional to the product of the scale length and the square root of the mass ratio. A substantial number of energetic ions also appear in the resonant region as a result of low frequency wave excitation.

*Work supported by USDOE DE-AM03-76SF00010 PA26, Task III.

Limiting Beta of ℓ=2 Stellarators With No Net Current

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New York University

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ABSTRACT

Using reduced, averaged, nonlinear MHD equations, we find finite beta, toroidal, ℓ=2 stellarator equilibria.[1] There is no net toroidal current on each flux surface, as required by finite resistivity. We concentrate on parameters corresponding to the W-VII-A and Heliotron-E experiments. We investigate stability to low mode number internal MHD modes, and find beta limits comparable to tokamaks. In fact, the low shear, long helical wavelength equilibria, such as W-VII-A, can be considerably more stable than tokamaks, with an easily accessible high beta ballooning stable regime.

Work partially supported by U.S. DOE Contract DE-AC02-76ERO 3077

1. H.R. Strauss and D.A. Monticello, PPPL-1738 (January 1981)

Poster Session
Please do not schedule Friday session

Monte-Carlo Heating Simulations of PDX and PLT*

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A Fokker-Planck simulation code 'MONSTER' has been developed to study ICRF and beam heating of Tokamaks. Monte-Carlo techniques are used to model RF and energy diffusion, pitch angle scattering and slowing down. The Monte-Carlo operators and various variance reduction techniques are similar to those of Goldston et al.[1]. Since the code can track particle trajectories in arbitrary plasma equilibria, we have investigated the effect of equilibrium shape, beam injection angle and toroidal field ripple on beam heating in PDX. Although there can be a large shine through loss with the present configuration, our results indicate that neither plasma shape, ripple, nor the near perpendicular injection angle give rise to significant energy loss from initially deposited beam particles. Thus the comparative ineffectiveness of PDX beam heating with respect to that of PLT, cannot be explained by these factors. We also present initial results for minority species ICRF heating in PLT which show the formation of the minority tail and the power deposition in the background plasma.

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*Work supported by Grumman Aerospace Corporation and the United States Department of Energy Contract #DE-AC02-76-CHO-3073

[1] R. J. Goldston, D. C. McCune, H. H. Towner, S. L. Davis, R. J. Hawryluk and G. L. Schmidt, Princeton Plasma Physics Lab Report PPPL 1753 March (1981).

1B12

RESONANT HELICALLY DISTORTED RELATIVISTIC ELECTRON BEAM EQUILIBRIA FOR FREE ELECTRON LASER APPLICATIONS*

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and

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ABSTRACT

The free electron laser holds considerable promise as a possible source of high-frequency radiation required for electron-cyclotron resonance heating of fusion plasmas in strong magnetic fields. The development[1] of a self-consistent kinetic description of helically distorted relativistic electron beam equilibria in combined transverse wiggler and uniform axial guide magnetic fields for free electron laser applications is extended herein. The development presented includes beam propagation under resonant conditions in which the doppler-shifted frequency in the wiggler field and the electron gyrofrequency in the guide field are approximately equal to each other. Radially confined Vlasov equilibria $f_b^0(C_\perp, C_h, C_z)$ which are functions of the three exact invariants are considered. Beam equilibria which correspond under non-resonant conditions to solid and hollow beams are examined. The behavior of the beam envelopes is determined. In the former (solid) case an equilibrium involves both closed and bounded open orbits in the two-dimensional transverse momentum space. In the latter (hollow) case equilibria typically involve larger radial excursions of the electron motion than under non-resonant conditions.

*Work supported by Office of Naval Research.

[1] Ronald C. Davidson and Han S. Uhm, "Helically Distorted Relativistic Electron Beam Equilibria for Free Electron Laser Applications," submitted to The Physics of Fluids.

1B13

Single Charged Particle Motion in Tokamak Geometries

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ABSTRACT

The usual theory of single charged particle motion in electric and magnetic fields require that for the magnetic moment to be an adiabatic invariant $\underset{\sim}{E} \cdot \underset{\sim}{B} = O(\varepsilon)$, where ε is the ratio of the particle larmor radius to the characteristic scale lengths of electric and magnetic fields. If $E \cdot B = O(\varepsilon)$ then the flux surfaces are also equipotential surfaces. We show that in a near axisymmetric geometry if B_P/B_T is of the order of the square root of ε or smaller, then a magnetic moment exists with essentially no restriction on $\underset{\sim}{E}$, other than that $|\underset{\sim}{E}|$ not be too large compared with $|\underset{\sim}{V}|\ |\underset{\sim}{B}|$. Thus, in the cases we treat the flux surfaces need not be equipotentials. We describe the orbits and we give the generalized guiding center Hamiltonian. We also indicate the implications of the analysis for anistropic equilibria including the effects of electric potentials.

Work supported by U.S. DOE Contract No. DE-AC02-76ERO 3077

Hybrid Simulation of Ion Beams and Rings in Background Plasma†

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and

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An initial version of CIDER, the Cornell Ion Dynamics and Electron Response code,[1] is now up and running. In this 2.5-dimensional hybrid code, beam and background ions are represented by particles of arbitrary charge to mass ratio, while electrons are represented by an inertialess fluid. All components of beam and plasma current are self-consistently accounted for. Fields are solved for in the quasineutral Darwin approximation. Electron thermal effects and ion-electron and ion-ion collisions are not included in the present version of CIDER, but will be added shortly.

The first results from CIDER, including code verification, field reversing ion ring runs, pinches, and ion beam transport in various configurations, will be presented. In addition, future plans and applications are discussed.

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

[1] A. Mankofsky, R. N. Sudan, J. Denavit, Bull. Am. Phys. Soc. 25, 1009 (1980).

POSTER SESSION

CURRENT GENERATION BY ELECTRON CYCLOTRON WAVE IN A TOROIDAL DEVICE*

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ABSTRACT

The possibility of dc tokamak operation has provided ample incentive for finding viable mechanisms for driving steady-state toroidal currents to replace inductively-driven currents. Two such mechanisms, both using electron cyclotron waves, have been proposed recently.[1,2] These mechanisms, although considered separately, occur simultaneously in an actual experiment on a toroidal device. Thus, for a quantitative evaluation of the feasibility of ECH current drive, a theory unifying these two mechanisms has to be developed. In this paper, such a theory will be presented.

In our theory, the wave heating effect is modeled by a quasilinear diffusion operator, and electron-ion and electron-electron collisions are taken into account using model collision operators. The resulting kinetic equation is solved in the banana regime and a closed form expression for the current induced is obtained. In the limit of zero inverse aspect ratio, the effect discussed in Ref. 2 is recovered. For nonzero inverse aspect ratio, a quantitative calculation based on the present theory predicts a reduction in the current induced from the slab model estimate. The physical reason for this reduction and the consequences of our findings will be discussed.

1. Ohkawa, T., General Atomic Report GA-A13847 (1976).
2. Fisch, N. J., and Boozer, A. H., Phys. Rev. Lett. 45 (1980) 720.

*Work supported by the Department of Energy, Contract DE-AT03-76ET51011.

~~Tokamak Plasma Heating Using Energetic Ion Beams*~~

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Energetic ion injection, as a method of heating tokamak plasmas to thermonuclear ignition[1], is investigated. The orbits of injected He^+ ions, including ripple effects, are obtained computationally. The guiding center orbits, of many α-particles produced by ionization, are then followed in order to calculate the plasma heating due to the collisional slowing of the α's. When the He^+ ion's energy and injection angle are chosen so that its guiding center passes through the plasma center, the heating profiles are peaked in the center of the plasma. In INTOR, an ion energy in the range 5-10 Mev is required. The angular tolerance is small; a 5° change in injection angle shifts the heating well away from the center, as does a moderate change in the assumed plasma current profile. At average densities greater than about $5\times10^{13}/cm^3$, He^+ ions injected in the equatorial plane tend to be ionized well before reaching the plasma center. However, injection at a point away from the equatorial plane allows a more direct path to the center; heating profiles with maxima in the center are then produced at average densities as high as $1.5\times10^{14}/cm^3$, although 15 Mev He^+ ions are required.

* Research sponsored by U.S. Department of Energy, Contract DE-AC05-76ET 53036 and Contract DE-AC05-80ER 53103 with Austin Research Associates.

1 J.M. Dawson and K.R. MacKenzie, U.C.L.A. Report PPG-470, March, 1980.

ROTATIONAL INSTABILITIES IN FIELD-REVERSED CONFIGURATIONS; RESULTS OF TWO-DIMENSIONAL HYBRID SIMULATIONS

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Rotational instabilities in field-reversed configurations are being studied using a two-dimensional hybrid simulation code. The code treats ions as particles and electrons as an inertialess fluid. Fields are described by the Darwin version of Maxwell's equations (i.e., the transverse displacement current is neglected) and the electron momentum equation, coupled by the assumption of quasineutrality. Ions are moved by the equations of motion. Linear weighting is used to determine forces, densities, and ion currents. The code has been applied to two configurations: (1) a tenuous high-current ion layer immersed in a dense background plasma, and (2) a field-reversed theta-pinch.

In field-reversed ion layers instabilities may arise due to a coupling of layer betatron oscillations with compressional Alfven waves in the background plasma. The hybrid simulations, as well as a numerical extension of previous theoretical work, have demonstrated that instabilities may occur in thin layers at levels of field-reversal below those previously predicted. This result implies that field-reversed ion layers must be very thick to be stable. The simulations show that instability growth causes heating within the layer, which results in the layer expanding, reducing the betatron frequency. The shift in betatron frequency prevents the resonant interaction of particles with the compressional Alfven waves, ending instability growth. After all instability growth has stopped the layer is still field-reversed, but much thicker. The final state appears to be relatively stable and is characterized by large electron currents and many non-axis-encircling ions.

The field-reversed theta-pinch has been simulated to study rotational instabilities driven by centrifugal forces. Unstable m=2 modes have been observed when the magnitude of the ion rotational frequency exceeds that of the difference between the ion and electron rotational frequencies, as expected. Preliminary results indicate linear growth rates comparable to those predicted by finite Larmor radius MHD and Vlasov-fluid models.

Work supported by ONR Contract No. N00014-17-C0578

Poster session requested

Sherwood Fusion Theory Conf., Austin, Texas, April 8-10, 1981

~~Abstract Submitted~~
for the 1981 Sherwood Meeting

Annual Controlled Fusion Theory Conference
Austin, Texas
April 8-10, 1981

D-D Tokamak Reactor Modeling. D. C. BAXTER, R.N. BYRNE, J. B. McBRIDE, S. TAMOR, C. E. WAGNER*.--This paper describes calculations of tokamak reactor operation using the D-D fusion fuel cycle. The code used to model the plasma is the one dimensional, time dependent tokamak reactor code MAK1, which we have extended to treat the reaction physics of the D-D fuel cycle (the two branches of D-D reactions, as well as D-T and D-He^3 reactions). The code calculates the radial profiles and the time evolution of the electron density and temperature, the ion densities for p,D,T, He^3 and He^4 and a common ion temperature and up to two impurity species. Power loss fractions in neutrons, diffusing plasma particles and heat, synchrotron and bremsstrahlung radiation are determined. These power splits provide the basis for a technology assessment of many of the reactor subsystems. A classical slowing down model for the fusion reaction products is used which calculates the non-local deposition of their energy as they thermalize. The code contains several options for the radial diffusion of particles and heat in order to assess the sensitivity of reactor size to plasma transport. As a reference plasma transport model, we use empirical scaling for electron particle and thermal transport, and neoclassical ion transport. Also included are the neoclassical effects of ripple on the ion thermal transport.

In order to assess the importance of profile effects on ignition points for D-D tokamaks, the results of our modeling calculations are compared to work of others who used global (spatially averaged) models.

*Present address INESCO, San Diego, California.

(x) Prefer Poster Session
( ) Prefer Standard Session
( ) No preference

David C Baxter
Signature of APS Member

David C. Baxter
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1981 SHERWOOD THEORY MEETING

Austin, Texas - April 8-10, 1981

EQUILIBRIUM AND TRANSPORT OF A COMPACT TOROID*

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We consider the equilibrium and transport of a compact toroid within the context of the $1\frac{1}{2}$-D transport model of Grad and Hogan. Since the geometric axis is included in the experimental configuration in a nontrivial manner (i.e., the current is nonzero there just after the formation) it is also included in the boundary of the calculation. Care is taken to handle the resulting singularities in an appropriate manner.

The transport calculation requires the equilibrium equation to be inverted with ν, μ given where $I = \frac{1}{A}\nu\psi'$, $p = \mu\psi'^{\gamma}$ and A and ψ' are to be determined self-consistently. To verify this procedure we analytically calculate ψ assuming $I = c\psi$, find the resulting ν, invert the equation numerically in the required form, and compare results.

We also report on the time evolution of the CT calculated by merging this equilibrium finder with a 1-D transport package.

*Work performed under the auspices of the USDOE.

1B20

Lower Hybrid Drift Instability; Theory and 2d Simulations

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The lower hybrid drift instability is being studied with both a 2-d electrostatic simulation code and a nonlocal theory. A slab configuration is used with a density gradient in x. In the initial equilibrium, the ion pressure gradient cancels the zeroth order ambipolar electric force. Since the characteristic frequency of the lower hybrid drift instability is much greater than the ion cyclotron frequency, the ions are treated as unmagnetized particles.

Simulations show good agreement of the measured growth rate and frequency with the results of local theory during the early stage of wave growth. At later times nonlocal effects become important, and a coherent mode structure developes. This normal mode is observed to propagate up the density gradient. The mean wave vector is $\underline{k}=k_y(-\hat{x}+\hat{y})$, in good agreement with our nonlocal theory.

At zero plasma beta and zero electron temperature, we found that the lower hybrid drift instability is stabilized by the local current relaxation occuring in two separate regions. The neighborhood of the point where the electrons have the greatest relative drift velocity is the most unstable region according to local theory. In this region the current relaxes by modification of the ion velocity distribution. However, in our nonlocal theory, the wave propagates into the plasma to a second region where the electron drift velocity equals the phase velocity of the most unstable wave. In this second region the electrons are in resonance with the wave and local current relaxation occurs by modification of the electron density profile.

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Submitted for poster session, Sherwood Theory Meeting, Annual Controlled Fusion Theory Conference, Austin, Texas, April 8-10, 1981.

Mechanisms for Energy Transfer from Electrons to Ions in Tokamaks

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A review will be given of various mechanisms which supplement particle collisions in the transfer of energy from electrons to ions in Tokamaks and which hence contribute to the anomalous electron energy loss. These mechanisms include:
(1) neoclassical transfer due to magnetic pumping cooling for electrons, combined with magnetic pumping heating for ions,
(2) inverse Landau damping cooling for electrons and Landau damping heating for ions due to electrostatic trapping,
(3) transfer due to drift waves,
(4) enhanced transfer via the first two mechanisms during sawtooth disruptions
(5) in impure plasmas, direct Ohmic heating of the hydrogen ions due to the ion bootstrap current J_{iz} driven by the radial ion heat conduction and
(6) transfer due to Mirnov oscillations.
The sum of the individually modest transfer rates is typically a substantial fraction of the electron heating rate and can explain much of the anomalous electron energy loss. In the outer regions of the plasma where T_i exceeds T_e, collisions transfer energy back to the electrons at a substantial rate.

This work is supported by DOE Grant DE-FG05-80ET 53088.

UCRL-85636

EFFECT OF PITCH-ANGLE COLLISIONS AND PHASE DECORRELATION ON DCLC TRANSPORT IN A MIRROR MACHINE*

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ABSTRACT

The effects of classical Coulomb pitch-angle diffusion on the DCLC-driven transport of thermal ions in mirror plugs are calculated. Pitch-angle diffusion produces a concomitant diffusion of the ion gyro-phase angle that is proportional to the ion-ion collision frequency, but which is enhanced by a geometrical factor involving the square of the axial magnetic scale length over the ion Larmor radius and is decreased by the ratio of the parallel to perpendicular ion energy. The resonant interaction of thermal ions in a plasma like 2XIIB with a drift-cyclotron-loss-cone (DCLC) wave can in turn be decorrelated by this diffusion. However, we find that the resulting resonant plateau transport is not significant. The transport is weak and cannot account for the energetic ions observed in 2XIIB in the energy range 25 keV to 40 keV. We have also analyzed the effects of wave-phase decorrelation on DCLC transport. Phase decorrelation, modeling bursting or finite bandwidth, drives stochasticity throughout velocity space wherever the effective wave amplitude remains finite. Anomalous transport to lower and higher energies becomes especially strong as the product of the rf-correlation time and the bounce frequency approaches unity, in agreement with the earlier result of Menyuk and Lee.[1]

Particle orbit studies with a Monte Carlo code verify the conclusions of our analysis of pitch-angle collision and phase decorrelation effects on DCLC. The wave-particle relative phase was randomized at discrete time intervals in the simulations to model phase decorrelation ion effects. Use of correlation times for the rf in the range suggested by 2XIIB data gave simulation results in which there was significantly enhanced transport and some ion energies approached 40 keV. Shorter correlation times on the order of the bounce time produced more transport and greater heating.

1. C. R. Menyuk and Y. C. Lee, Phys. Fluids 23, 2225 (1980).

*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.

POSTER SESSION

ROLE OF MAGNETIC HELICITY ON THE EVOLUTION OF THE MOST PROBABLE EQUILIBRIUM PROFILES FOR THE REVERSED FIELD PINCH

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The rugged invariant, magnetic helicity H, plays a central role in theories[1,2] concerning the relaxed states of an RFP. It is shown[3] how H can be determined experimentally.

The most probable states of Ambrosiano and Vahala[4] - which proposes a statistical method for determining the evolution of MHD equilibrium profiles given the global constraints of toroidal flux Φ, toroidal current I, magnetic energy E and H - is extended to allowing a further constraint to be imposed: the experimentally-controllable value of B_z at the conducting wall. (Φ and I are the other controllable experimental parameters while E is deduced from probe measurements.) Numerical solution of these equations, with $J_z \simeq 0$ at the wall, will be presented together with the effect of various values of E and H at fixed Φ, I, $B_z(1)$ on the RFP profiles.

The theory can be extended to include fluid flows as well as compressibility.

Comparison will be made with experimental data from HBTX and ETA-BETA II.

[1]J. B. Taylor, Phys. Rev. Lett., 33, 1139 (1974).

[2]D. Montgomery, L. Turner and G. Vahala, Phys. Fluids 21, 757 (1978).

[3]W. H. Matthaeus and C. Smith, to be published.

[4]J. Ambrosiano and G. Vahala, Bull. Am. Phys. Soc. 25, 1027 (1980).

WAVE-DRIVEN CURRENTS IN A TORUS*

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MHD equilibrium calculations for tokamaks conventionally require knowledge of the pressure and diamagnetism profiles, which often are varied to identify optimal equilibria. Since in principle the profiles are taken from transport calculations, there is considerable uncertainty associated with them. A simplification occurs in the case of wave-driven currents, for which the equilibrium is still described by the Grad-Shafranov equation, but for which the parallel current density can be computed from the spatial damping of traveling plasma waves in the presence of a specified pressure profile. The resulting parallel current density can then be combined with the MHD constraint, $J_\parallel = -B^{-1}F\ p'(\psi) - \mu_0^{-1}BF'(\psi)$, to yield a diamagnetism profile $F(\psi)$ appropriate for input to the MHD equilibrium calculations. To this end, we have formulated a quasilinear version of the drift kinetic equation which includes the effects of spatial gradients. These effects are introduced via nonuniform wave damping (e.g. lower hybrid damping localized within resonance cones) and field line bending due to the toroidal geometry. Using this drift kinetic equation with a large aspect ratio and poloidally uniform wave damping, we show that $J_\parallel$ is correct to first order in A^{-1} if $F(\psi)$ is taken from the solution to the cylindrical current drive problem. The connection with the Shafranov shifted-circles equilibrium is also pointed out. Examples of toroidal equilibria consistent with current drive results will be presented.

WAVE ENHANCED PRODUCTION OF RUNAWAY IONS IN TOKAMAK PLASMAS AND ITS IMPLICATION FOR A TWO-COMPONENT REACTOR

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Because of the effective $Z_{eff} > 1$ or the toroidal effect in a tokamak, there is an effective electric field on the hydrogen ions $E^* = E\left(1 - \frac{1}{Z_{eff}}\right)$ leading to possible ion runaway.[1] Due to the electron drag, however, the runaway ion may reach a terminal velocity $v_2 = eE^*/m\nu_e < v_e$ provided $E^* > E_c(m/2Z_{eff}^2 M)^{1/3}$, where ν_e is the electron-ion collision frequency, $E_c = 4\pi n_i Z_{eff}^2 e^3 \ln\Lambda/kT_e$ is a critical field. The runaway ion population however is proportional to $\exp\left[-E_c/4E^* - \left(E_c/E^*\right)^{1/2}\right]$ and is therefore small. Recently, it is shown that waves can greatly enhance the runaway electron production[2]. The effects of ion waves on the runaway ion production is considered here and the runaway ion population is shown to be greatly enhanced by wave quasilinear diffusion

$$\exp\left[-E_c/4E^*(1 + D_o) - \left(E_c/E^*(1 + D_o)\right)^{1/2}\right]$$

where D_o is the ratio of quasilinear to collisional diffusion coefficients. Implication to plasma heating, ion beam production, and two-component reactor will be discussed.

*Work supported by the Department of Energy.

[1] H. P. Furth and P. H. Rutherford, Phys. Rev. Lett. 28, 545 (1972).
[2] C. S. Liu, Z. G. An, D. A. Boyd, Y. C. Lee, L. Muschietti, K. Appert, and J. Vaclavik, submitted to Phys. Rev. Lett.

MAGNETIC TRAPPED PARTICLE MODES

M. Rosenbluth

At very low frequencies ($\omega \lesssim \omega_d$) plasma motion becomes dominated by magnetic gradient and curvature drifts rather than the familiar $E \times B$ drifts. The system may then become unstable to pure magnetic perturbations when $\nabla p/B\nabla B$ is negative and large, as drifting particles collect in regions of low magnetic field making $dP/dB^2 < 0$. Such a situation arises when particles are trapped in regions of unfavorable curvature and β is large enough to reverse the field gradients (magnetic drifts).

A quantitative treatment is based on newly developed kinetic energy principles[1,2]. It is shown that for systems such as collisionless tandem mirrors instability may often be expected when β in the central cell is large enough to reverse the magnetic drifts, and the plasma satisfies either of the line-averaged conditions: $\int K d\ell/rB^2 < 0$ or

$$\partial p/\partial\psi \int d\ell/B^5 - 20 \int (K/B^4 r)\, d\ell + 63/4 \left[\int (K/B^3 r) d\ell \right]^2 / \int (K/B^2 r) d\ell > 0.$$

Here K is the curvature (negative K implying unfavorable curvature), and $\partial p/\partial\psi < 0$. Some discussion will be given of modifying effects of ambipolar fields, collisions, and finite gyroradius effects.

[1] Antonsen, Lane and Ramos (submitted to Phys. Fluids).

[2] Van Dam, Lee, and Rosenbluth (submitted to Phys. Fluids).

This work supported by DOE Grant No. DE-FG05-80ET 53088.

Symmetries and Preferred Constants of the Motion

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ABSTRACT

Equations describing physical systems often have an infinite number of constants of the motion, e.g., inviscid incompressible fluid dynamics, ideal MHD, etc. If because of some additional effects, like turbulence, the equations can only be viewed as an approximation, with part of the information to be discarded, one may want to accept only some of the constants of the motion as "good." A similar question arises when one wants to approximate the equations, say by a finite-difference scheme, and it has to be decided which conserved quantities should be kept. (In plasma turbulence the magnetic helicity $\int \underset{\sim}{A} \cdot \underset{\sim}{B}$ is a favorite.[1])

We offer the following principle: if the original system is invariant under some time-independent transformation (Galilean, scaling and others) the set of selected constants of the motion should transform into functions of the untransformed constants (so no new conserved quantity is generated). Our approach is not arbitrary as the standard "rugged invariant" argument[2] is, and offers a hierarchy of conserved quantities to be kept for better and better approximations. Examples will be shown.

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1. J.B. Taylor, Phys. Rev. Lett. 33, 1139 (1974)

2. R.H. Kraïchman, Phy. Fluids 10, 1417 (1967)

1981 SHERWOOD THEORY MEETING

~~Austin, Texas - April 8-10, 1981~~

MAGNETIC FIELD ERRORS IN THE RFP FROM POLOIDAL FLUX GAPS*

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In toroidal discharges, a toroidal voltage is usually applied across one or more poloidal gaps, through which the poloidal flux then enters the discharge producing a sheared magnetic geometry. Such gaps constitute an irreducible source of field error, with consequences for particle and energy loss from the plasma. In particular, a train of these gaps can resonate with the $q = 0$ flux surface near the wall during quiescence in the Reversed-Field Pinch (RFP). Our ultimate objective is to quantify the nature of these field errors in actual RFP devices.

In the present study, we calculate the field perturbations produced by a single gap in the presence of an RFP plasma configuration. We show how this result is immediately relevant to the calculation of the field errors from a train of such gaps. In the small gap limit, we show that the field distribution is the same as that due to a current dipole of a certain characteristic strength. Results will be presented for a variety of gap widths and positions of the reversal surface, and these results will be compared to those for the case of a gap in vacuum.

*Work performed under the auspices of the USDOE.

POSTER SESSION REQUESTED

SIMULATION OF THE QUASI-STATIC FORMATION OF A SPHEROMAK USING COMBINED Z- AND θ-PINCH TECHNIQUES*

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In the proposed MS-1 experiment, a spheromak configuration will be generated using a combination of z- and θ-pinch techniques. In comparison with PS-1, the new experiment will have lower density (10^{14} - 10^{15} cm^{-3}) and higher fields (external poloidal field $\gtrsim$ 10 kG), and a longer formation time ($\simeq$ 20 μsec), implying a quasi-static formation. The formation phase is modeled by a 2-D resistive, finite β MHD code, including the effects of impurity radiation and anisotropic heat conductivity and applying realistic non-conducting boundary conditions. Classical values for resistivity and parallel heat conduction have been used, while the perpendicular heat conductivity has been taken from Alcator scaling. With a suitable filling density profile achieved by gas puffing, and assuming 3% carbon and 0.5% oxygen impurities, we find that a spheromak configuration with a peak density of 3×10^{15} cm^{-3} is formed and heats to about 100 eV in 20 μsec.

*Work supported by the Department of Energy.

Electron Currents Effects in Field-Reversed Mirror Dynamics*

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The effects of electron currents on FRM start-up via neutral-beam injection are under study using a 1-D radial hybrid code. Although "line-tying" eliminates electron currents on open field lines, electrons may heat up on closed field lines, increasing their diamagnetic current and decreasing ion drag. Also, charge separation between large orbit ions and fluid electrons produce a radial $\vec{E}$-field, driving an $\vec{E}_r \times \vec{B}$ electron current. Finally, fluid equations indicate that electron currents can prevent the transition from open to closed field lines unless an ion impurity is present (Ohkawa currents[1]) or azimuthal symmetry is broken ("magnetic pumping"[2]).

The 1-D code models the plasma as azimuthally symmetric with no axial dependence. The time evolution of the distribution function for the ions from the beam is followed by a multi-group treatment in energy and canonical angular momentum. This distribution evolves due to collisions with electrons, inductive electric field, and the neutral beam source. The ion current and density profiles are constructed from the ion orbits corresponding to each group. Electrons are treated as a fluid with continuity and energy equations, flux conservation, and a time-differentiated Grad-Shafranov equation that includes the ion current. A Lagrangian mesh in flux coordinates is used. Because of the high electron conductivity along field lines, the electron temperature and density are set equal on the two radii of a closed flux surface. The fluid equations are collisionless, with no electro-static fields, but studies to include these effects are now underway.

1. D. E. Baldwin and M. E. Rensick, Comments Plasma Phys. Ctr. Fusion, 4, No. 2, 55-63 (1978).

2. J. Hammer and H. Berk, Butl. APS, 24, 2Q3 (1979).

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GYROELASTIC FLUIDS*

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ABSTRACT

A systematic study is made of a simple scale model in three dimensions of a guiding center plasma within the purview of gyroelastic (also known as finite-gyro-radius or finite-angular-momentum-density) magnetohydrodynamics. The nonlinear system sustains a particular symmetry called isorrhopy as a result of which drift oscillations and fluid oscillations are decoupled. Isorrhopic equilibria are analyzed first within the framework of geometrical optics, resulting in local dispersion relations and ray constants. A general scheme is then developed to evolve an arbitrary linear perturbation of a screwpinch equilibrium as an invertible integral transform over the complete set of generalized eigenfunctions defined naturally by the equilibrium. Details of the structure of the function space and the associated spectra are elucidated. Features of the global dispersion relation owing to the presence of gyroelastic stabilization are revealed. An energy principle is developed and applied to study the stability of the tubular screwpinch.

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Drift Mode Analysis of the Tandem Mirror

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Within the long-thin, axisymmetric approximation, the Tandem Mirror system is analyzed for drift mode stability. From the three basic system parameters, (i) plasma pressure β, (ii) inverse aspect ratio $\varepsilon = r/L$ and (iii) gyroradius ρ/r, we show that the electromagnetic axial eigenvalue problem[1] has three forms according to the relation of β with respect to $\beta_1 = \varepsilon^2$ and $\beta_2 = \varepsilon$ for $\Delta\theta = \rho L/r^2 \sim 1$. For $\beta < \beta_1$ the polarization of the drift modes is electrostatic and stability conditions for the odd and even axial eigen functions are derived. For $\beta > \beta_2$ the polarization is MHD for two branches of the dispersion relation and purely electromagnetic for the electron drift wave branch. For the intermediate pressure range $\beta_1 < \beta < \beta_2$, the system is described by an intermediate polarization with the electrostatic and parallel inductive equation governed by coupled second order equations. A local analysis in the bad curvature transition region L_t shows that the electrostatic instability driven by the ion pressure gradient with a maximum growth rate $\gamma_m \sim \varepsilon^{1/2}$ at finite azimuthal mode numbers for $\beta \sim \beta_1$ transforms into the total pressure gradient driven MHD with $\gamma_m \sim \varepsilon^{1/2}$ at the small azimuthal mode numbers.

The destabilizing role of the radial electric field and the nature of the anomalous radial transport have also been investigated.

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This work was supported by the U.S. Department of Energy Grant No. DE-FG05-80ET 53088.

UCRL-

SCALING LAWS FOR BEAM HEATED FIELD REVERSED MIRRORS

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ABSTRACT

Future compact torus experiments of the β-II and CTX family should elucidate the transport laws for compact torus plasmas. The present experiments seem to be limited by time radiation from impurities and so it is difficult to distinguish between various theoretical models. Classical transport shows that a compact torus should classically heat close to the MHD-limit, set by low toroidal mode number modes. The Alcatov model of electron thermal transport is much higher than classical and beam heating is needed to get to the beta limit to heat the plasma quickly in an experiment to explore any advantages of FLR stabilization, and to provide possible Ohkawa current in steady state.

Point model and 2D adiabatic heating models explore scenarios up to small (20-50 MW) reactors.

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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.

POSTER SESSION

Effect of Turbulent Diffusion on Collisionless Tearing Instabilities

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In a plausible model of high temperature tokamak kinetics, Coulomb collisions are negligibly rare, while fine scale turbulence due to microinstabilities (for example drift waves) provides significant dissipation.[1] Using the sheared slab model, we obtain modifications to the kinetic electron response due to drift wave turbulence[2] (the effect of magnetic braiding was considered in ref. 3). The resulting integral equations for the fields, including electrostatic terms, are solved by variational-perturbative techniques.[4] The effect of turbulence on the tearing mode dispersion relation depends of the parameter

$$\delta = \left(\frac{\omega_c}{\omega}\right)^3 \left(\frac{x_e}{w}\right)^2$$

where ω_c is the turbulent decorrelation frequency, ω is the mode frequency, $x_e = \omega/k'v_e$ is the electron resonance width, and w is the width of the tearing mode parallel electric field. Because $w \gg x_e$ for $m \geq 2$ collisionless tearing modes[4] and typically $\omega_c/\omega \ll 1$, the effect on the dispersion relation is weak. For m=1 tearing modes, however, $w \ll x_e$ and the turbulence is more important.

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

[1] S.P.Hirshman and K. Molvig, Phys. Rev. Lett. 42, 648 (1979).

[2] P.H. Diamond and M.N. Rosenbluth, to be published.

[3] M. Kotschenreuther, J.A. Krommes, and C. Oberman, Bull. A.P.S. 25, 1034, (1980).

[4] S.M. Mahajan, et al, Phys. Fluids 22, 2147, (1979).

Internal Kink And Collisionless Magnetic Reconnection In Finite-Beta Toroidal Plasmas*

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A theory of m=1 internal kink and reconnecting modes in finite-beta toroidal confinement configurations is presented. The global MHD structure of the modes is obtained by starting with the theory of internal kinks in low-beta toroidal plasmas[1,2] and developing one that represents the relevant modes in finite-beta ($\beta_p > 1$) configurations. These modes are primarily driven by the pressure gradient, which also induces important changes in the equilibrium configuration. The coupling to the m=0 and m=2 mode harmonics is properly taken into account.

In conditions where no ideal MHD instability of this kind can be found, we consider a collisionless layer around the q=1 surface, where the magnetic field lines may reconnect, depending on the structure of the global mode. The growth rates of the toroidal reconnecting mode are found by an asymptotic matching of the MHD solution to solutions of the collisionless kinetic equation across this layer[3], taking into account the existence of the several asymptotic regions.[4]

[1] M.N. Bussac, R. Pellat, D. Edery and J.L. Soule, Phys. Rev. Lett. 35 (1975), 1638.

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[3] B. Basu and B. Coppi, Massachusetts Institute of Technology RLE Report PRR-79/15 (Cambridge, MA, 1979). To be published in Phys. of Fluids.

[4] B. Coppi, J.W-K. Mark, L. Sugiyama and G. Bertin, Ann. Phys. 119 (1979), 370.

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1981 SHERWOOD THEORY MEETING
Austin, Texas - April 8-10, 1981

KINETIC EFFECTS ON THE TILTING MODE IN FIELD REVERSED CONFIGURATIONS*

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A formulation for studying kinetic effects on the stability of the tilting mode in FRX geometry is presented. First an energy functional representation (dispersion functional) of the linearized Vlasov-fluid model is developed by using Lionville eigenfunctions to represent the ion orbit integrals. The assumption of small Larmor radius then leads to an explicit separation of the dispersion functional into four parts, representing the effects of MHD driving forces, FLR stabilizing effects, fluid kinetic energy, and resonant ion effects. The use of this dispersion functional for studying the tilting mode proceeds by considering the form of the tilting mode displacement, primarily a rigid axial field line displacement. In the limit of highly elongated equilibria, part of the resonant ion term dominates the other three terms. In particular it is the trapped ions in the end regions of the configuration that give rise to this formally large stabilizing effect. Since this resonant ion term is the leading order term in the elongation a/b, it must be minimized to zero. This is affected by imposing a specific constraint on the displacement eigenfunction, which results in the two independent components of displacement being expressed in terms of a single arbitrary function of polodial flux and distance along a field line. The dependence of this function on s, the distance along a field line, is assumed to be a rigid axial displacement, which is known to minimize MHD δW for local modes. The flux dependence of the function is then determined by minimizing δW which involves solving a second order differential equation in Ψ. The eigenfrequencies of the mode are determined by substituting the resulting displacement into the dispersion functional, performing the necessary orbit integrations and then numerically iterating on the eigenvalue.

*Work performed under the auspices of the USDOE.

POSTER SESSION REQUESTED

NONADIABATICITY IN AN AXISYMMETRIC MIRROR WITH AN INTERNAL RING*

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This paper discusses a calculation of the nonadiabaticity of the magnetic moment in a mirror which is stabilized by an internal current carrying ring. This configuration has the advantage of axisymmetry, but it suffers through the existence of a field null. The goal of this calculation is a reliable estimate of the size of the nonadiabatic region. Results were obtained both by use of a formula derived for the pure axisymmetric quadrupole cusp and by computation of particle orbits in a typical internal ring mirror configuration. From these results it is concluded that the magnetic moment is adiabatic to better than one part in 10^5 for particles on flux surfaces which are farther than 10 Larmor radii from the symmetry axis when measured at the mirror throat.

*Work supported by the United States Department of Energy.

NOTE: To be placed adjacent to "MHD Equilibrium and Stability of Axisymmetric Tandem Mirror Plug with an Internal Ring" by A. E. Walstead and E. A. Adler.

MHD Equilibrium and Stability of Axisymmetric Tandem Mirror Plug with an Internal Ring*

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Axisymmetric tandem mirror configurations have several advantages over conventional designs with quadripole plugs: 1) improved central cell betas due to shortened and symmetric transition regions between the plugs and central cell; 2) the absence of anomalous radial transport due to field asymmetry. On the other hand, recently proposed[1] axisymmetric tandem configurations have field nulls on open field lines, which raises questions about nonadiabatic losses and MHD stability. We have studied the finite beta equilibrium and stability of a particular axisymmetric plug that uses an internal ring for MHD stability and possesses a class of absolutely confined ions that can support plasma pressure in the immediate vicinity of the separatrix and nulls. The question of nonadiabaticity in regions adjoining the immediate neighborhood of the separatrix and null has been discussed by Adler.[2] The stability calculations yield beta values of 17% for the plug, where beta is defined in terms of the maximum pressure in the plug and the maximum magnetic field in the mirror throat on axis. This beta value represents a 70% improvement over calculations based on the vacuum field alone and should be regarded as a lower bound on the true beta of the configuration.

*Work supported by USDOE.
1. B. G. Logan, "Comments on Plasma Physics & Controlled Fusion" 5, 271 (1980); G. Shuy, et al., ibid.
2. See E. A. Adler this proceedings.

NOTE: To be placed adjacent to "Nonadiabaticity in an Axisymmetric Mirror with an Internal Ring" by E. A. Adler.

1981 SHERWOOD THEORY MEETING
Austin, Texas - April 8-10, 1981

CONSOLIDATED CONTINUED FRACTION TECHNIQUE FOR SOLVING THE DIRECT INTERACTION APPROXIMATION*

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Contrary to the eddy viscosity description of fluid turbulence, transient trapping in the fluctuating potential wells of turbulent plasma waves implies the existence of nonlinear normal modes, which are not simply broadened versions of the linear resonances.

A selfconsistent renormalized approximation, such as the Direct Interaction Approximation (DIA), while containing such phenomena in principle, is very difficult to manipulate. In collabotation with D. F. Dubois, a truncated continued fraction representation of solutions to the DIA has been constructed, which allows for the explicit identification of these nonlinear normal modes. This technique is illustrated for a nonlinear Schrodinger equation.

*Work performed under the auspices of the USDOE.

EFFECTS OF A STRONG MEAN MAGNETIC FIELD ON MHD TURBULENCE

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Most of the theory of high-Reynolds number MHD turbulence relies on several assumed symmetries of the statistics of the fluctuating fields: spatial homogeneity, rotational isotropy, mirror (reflection) invariance, and often, temporal stationarity. While these symmetry assumptions vastly simplify the theory, they interfere with its applicability to many situations in both CTR plasmas and space plasmas. Externally-imposed mean magnetic fields can destroy rotational isotropy, and net mean currents driven along those mean magnetic fields can destroy reflection invariance. Here we investigate the effect of a very strong, externally-imposed dc magnetic field on incompressible MHD turbulence. The most important effect appears to be the introduction of a near-two dimensionality, which becomes perfect in the limit in which the ratios of fluctuating magnetic field and velocity field to the dc magnetic field approach zero. Several consequences for the fluctating spectrum emerge: (1) parallel correlation lengths become much greater than perpendicular ones; (2) fluctuating $\underset{\sim}{B}$ and $\underset{\sim}{v}$ fields become nearly perpendicular to the mean magnetic field direction; (3) frequencies in the fluctuation spectra become much less than the reciprocal of the Alfvén transit time; and (4) the lowest-order dynamics become describable by the equations of two-dimensional MHD, previously extensively investigated. These predictions are fulfilled to varying degrees by measurements in the Zeta pinch device, the Macrotor tokamak, and in the solar wind.

1981 SHERWOOD THEORY MEETING
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ON A HELICAL OHMIC STATE FOR REVERSED-FIELD PINCHES

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The mechanics of selftriggered field reversal in the set-up phase of an RFP are investigated. In particular, the reversed-field pinch is viewed as the nonlinear saturated state of a helical resistive mode. A quasi-linear treatment is adopted for the region outside the saturated mode island. On the other hand, a nonlinear model including the effect of resistive flow has been developed to describe the island itself.

EBT TRANSPORT AND AMBIPOLAR POTENTIAL FORMATION WITH RAPID LOSS OF HIGH ENERGY IMPURITY IONS*

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Density profiles for neutral impurity atoms and impurity ions of a single charge state are calculated as functions of radius in a 1-1/2 D transport calculation for the EBT toroidal plasma. Ad hoc energies and transport rates are assumed for the impurity ions consistent with spectroscopic measurements. Steady-state solutions show potential well depths on the order of the impurity ion temperature divided by its charge ($e\phi \gtrsim 100$ ev). Also classical viscosity due to the large gryoradius of the impurity ions limits shear in the poloidal drift velocity. Therefore potential profiles tend to be more parabolic and the plasma rotates more nearly as a rigid body than would be expected from simple neoclassical theory with no impurities present.[1]

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

[1]E. F. Jaeger et al., Nucl. Fusion 19, 1627 (1979).

Stability Analysis of Straight Stellarators

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The recent interest in stellarators caused us to re-examine the stability criterion[1] of the straight $\ell = 2$ and $\ell = 3$ stellarators. The stability limit is calculated balancing the stabilizing effect of shear against the averaged, bad curvature of the perturbing helical field. The effects of both diamagnetic current and the parallel current arising from the geodesic curvature on stability were also included. The stability limits were evaluated numerically and for small helical fields by an analytic expansion. The numerical calculation and analytical estimate both show these current effects are of the order of 10% of the main destabilizing curvature effect. The numerical and analytic results on limiting β's were in very good agreement. The resultant value for average β was found to be 2-3%. The usual assumption that the peak β-value is approximately δ^2 where δ is the distortion from circularity of the magnetic surface is found to be valid. However, the previous estimate has given a δ value of 1/3. It was found that the δ is limited to $1/3(3)^{1/2}$ due to the appearance of the separatrix.

This work was supported by US Department of Energy Contract No. DE-AC02-76-CHO3073.

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[1] J. M. Greene and J. L. Johnson, Plasma Physics 10, 729 (1968).

A Moments Approach to Free Boundary Two-Dimensional Tokamak Transport and Axisymmetric Resistive Stability*

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The general formulation for two dimensional transport of tokamak plasmas[1] is numerically implemented by representing the cartesian coordinates $x(\psi,\theta)$ and $z(\psi,\theta)$ as truncated Fourier series in the poloidal angle θ with finite differences in the flux surface label ψ. The equilibrium constraint is imposed through a system of ordinary differential equations obtained from a variational principle.[2] These moment equations allow for asymmetry with respect to the midplane. They are solved as a system of second order boundary value problems, with derivative boundary conditions at the origin explicitly prescribed. A coupled vacuum solution links the plasma solution to discrete currents in external conductors. Circuit equations for the conductors close the system. The formulation described here provides a very efficient method for the study of the axisymmetric evolution of tokamaks on the resistive time scale.

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*This work was supported by the United States Department of Energy Contract No. DE-AC02-76-CH03073.

[1]S. P. Hirshman and S. C. Jardin, Phys. Fluids 22, 731 (1978).
[2]L. L. Lao, S. P. Hirshman, and R. M. Wieland, ORNL/TM-7616 (1981).

POSTER SESSION

SYNCHROTRON RADIATION EMISSION FROM AN ANISOTROPIC ELECTRON DISTRIBUTION FUNCTION*

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In the relativistic rings of the Elmo Bumpy Torus experiment, and in the planned thermal barriers for tandem mirror experiments the electron distribution function will be anisotropic with the average perpendicular energy much larger than the average parallel energy. In the perpendicular direction the electrons will be essentially collisionless and can be described by a loss cone distribution. Electron synchrotron radiation is important as a diagnostic tool and as an energy loss mechanism for these plasmas. In this paper a study is presented of the electron synchrotron spectrum emitted by a homogeneous plasma with a loss cone electron distribution function with $T_{\perp} \gg T_{\parallel}$. The dependence of characteristics of the spectrum on parameters of the distribution function and on the angle of emission with respect to the magnetic field direction is examined.

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UCRL-85628

THEORY OF FLUX AMPLIFICATION IN PLASMA GUN PRODUCED COMPACT TOROIDS

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ABSTRACT

The minimum energy theory of J. B. Taylor[1] is applied to compact toroids produced by a coaxial plasma gun. Use of the conservation of the magnetic helicity permits a complete determination of the equilibrium in terms of gun and circuit parameters. In particular, an expression for the flux amplification factor, ϕ_f/ϕ_i (ratio of poloidal flux in the final state to poloidal flux threading the gun) is found. Typical experimental values of $\phi_f/\phi_i \cong 2.6$ have been observed in comparison to a theoretical value $\phi_f/\phi_i \cong 2.8$. Other implications of the theory, e.g., formation by multiple pulses, will be discussed.

1. J. B. Taylor, Phys. Rev. Lett. 33, 1139 (1974).

*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.

LIKE-PARTICLE AND TEST-PARTICLE TRANSPORT

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The theory of neoclassical transport in arbitrary geometry has been formulated, assuming only the existence of three invariant actions, J_1, J_2, J_3, with well ordered frequencies $\omega_1 >> \omega_2 >> \omega_3 >> \gamma$. The theory is based on a generalized Fokker-Planck equation of the form

$$\frac{\partial f(\underline{J})}{\partial t} = C_J(f,f) = -\underline{\nabla}_J \cdot \underline{\Gamma}_J$$

which directly scatters the actions.

The third action, J_3, is radial in the sense that the particle energy is predominately a function of J_1 and J_2. Accordingly, J_3 is scattered at a slow rate relative to J_1 and J_2, direct expansion of the kinetic equation in this small parameter generates the transport equations.

A sufficient condition is derived for the vanishing of the particle flux due to like-particle collisions, namely that J_3 (the radial coordinate) minus an arbitrary function of J_1 and J_2 be a function which is annihilated by the collision operator. This condition is satisfied in axisymmetric systems. Conditions under which a test-particle calculation of transport is a good approximation are discussed. Application of the formalism to tandem-mirror machines is considered.

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

POSTER SESSION

The Role of "Passing" Electrons In the Energy Balance of Tandem Mirror Plasma*

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In a standard Tandem Mirror device the density and temperature of the electrons in the plugs are sufficiently distinct from those in the central cell that an electrostatic potential difference is established to provide confinement for the particles in the central cell. Electrons in the plugs can, of course, escape from the potential well into the central cell thereby transferring energy to the electrons in that region via the Pastukhov prescription. In this paper we focus our attention on electrons that flow in the opposite direction, namely, central cell electrons that enter the plugs. These particles get accelerated by the potential across the plug to the end of the device where the plasma potential drops below its value in the central cell. At that point most central cell electrons are reflected back across the plugs into the central cell once more. These "passing" electrons interact with the plug electrons and exchange energy with them while transiting. For these particles we derive expressions for the density and average kinetic energy, and using a relativistic slowing down formula, we calculate the power flow from the central cell to the plugs. We find for a reactor grade plasma that the energy flow from the plugs to the central cell is reduced by about 60% as a result of the energy flow in the opposite direction due to the passing electrons. This effect which tends to widen the gap between the electron temperatures in the plug and central cell could have a significant effect on the maintainability of the confining potential.

*Work supported by DOE

Renormalized Lie Perturbation Theory

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A Lie operator method for constructing action-angle transformations continuously connected to the identity is developed for area preserving mappings. By a simple change of variable from action to angular frequency a perturbation expansion is obtained in which the small denominators have been renormalized. The method is shown to lead to the same series as the Lagrangian perturbation method of Greene and Percival, which converges on KAM surfaces. The method is not superconvergent, but yields simple recursion relations which allow automatic algebraic manipulation techniques to be used to develop the series to high order. It is argued that the operator method can be justified by analytically continuing from the complex angular frequency plane onto the real line. A resonance overlap criterion is developed using these theories. It is shown that the breakage of KAM surfaces is due to the overlap of high-order resonances. The convergence properties of the Fourier series for the angle variable are also explored.

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1981 SHERWOOD THEORY MEETING

~~Austin, Texas - April 8-10, 1981~~

ICRF OSCILLATIONS OF AN INHOMOGENEOUS PLASMA CYLINDER*

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We have derived a dispersion differential equation suitable for studying free and forced oscillations of a radially inhomogeneous plasma cylinder in the ion cyclotron range of frequencies (ICRF). Solving the differential equation, subject to appropriate boundary conditions, yields global eigenmodes of the cylindrical configuration; thus, our description embraces both the geometry and the physics relevant in the ICRF. The derivation begins with the equations of the Vlasov (ion)-fluid (electron) model. An approximate solution of the ion Vlasov equation is obtained analytically for a general screw pinch equilibrium by restricting the ion gyroradius to small, but finite, values. However, the frequency of oscillation is not assumed to be small compared with the ion cyclotron frequency, and the pitch of the magnetic field lines is not restricted to large values. Thus, we have generalized and extended the theory of finite ion gyroradius effects by including ion cyclotron damping, arbitrary diffuse cylindrically symmetric equilibrium profiles, and other effects. The approximate solution of the ion Vlasov equation together with the Ampere equation yields the dispersion differential equation. The solutions of the equation explicitly exhibit two different length scales: an MHD length scale (the pinch radius) and a microscopic scale (the ion gyroradius).

In the limit of vanishingly small ion gyroradii, our model reduces to the guiding center plasma model.

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Kinetic Effects on Ballooning Mode Beta Criteria in Tokamaks*

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The influence of kinetic effects on the limiting beta for MHD ballooning modes in tokamaks is investigated. We first systematically study the stabilizing contribution of the ion diamagnetic drift by appropriately modifying an MHD ballooning mode code which has been properly interfaced with numerically computed (as opposed to idealized) tokamak equilibria. We then go on to employ a very comprehensive kinetic code[1] which is also interfaced with general equilibria and which includes other basic kinetic effects such as wave-particle resonances, trapped particles, etc. In particular, we focus attention on the application of these studies to the ISX-B experiment where beta values as high as 10.5% on the magnetic axis have been observed.

* Work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

1 G. Rewoldt, M. S. Chance, W. M. Tang, and E. A. Frieman, Bull. Am. Phys. Soc. 25, 925 (1980).

Poster

Please schedule this poster for Thursday, April 9.

Numerical Studies of MHD Modes with Singular Behavior*

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The inclusion of finite element expansion functions with the correct asymptotic behaviors near rational surfaces, together with mesh refinement techniques, make the PEST code a powerful tool for the study of ideal and resistive MHD instabilities. For ideal MHD very accurate results are obtained with relative ease. This is particularly significant for the evaluation of marginal points in β-optimization studies where, previously, extended exploration of parameter space was prohibitively expensive. Accurate analysis of the internal kink is also quite straightforward. For resistive modes proper treatment of the singularities enables a calculation of $\underline{\underline{\Delta}}'$ for a boundary layer calculation of resistive growth rates. We present results illustrating the application to the study of marginal stability points, to the internal kink mode and to the evaluation of Δ'.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

Poster Session

ELECTROSTATIC EFFECTS ON VARIATIONAL PRINCIPLES FOR ANISOTROPIC PLASMAS*

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The kinetic energy principle is modified by the presence of an equilibrium electrostatic potential and the inclusion of the quasi-neutrality condition. By identifying terms that are fluid-like (local) and kinetic (non-local), one can express the change in potential energy, δW, in a form which is both variational and minimizing and also displays clearly the electrostatic effects on the various free energy sources. The kinetic energy principle determines the stability of the plasma to perturbations that grow on the time scale associated with the streaming of particles along field lines. Recently, a new variational principle has been proposed[1,2] which determines the stability of the plasma to perturbations that grow on the time scale associated with the drifting of particles across field lines. The modifications of this principle due to electrostatic effects will also be considered.

*Work supported by the Department of Energy.

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DOES BALLOONING MODE LIMIT THE TOKAMAK β ?

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In tokamak devices, MHD ballooning mode may set the limitation of plasma β value, $\beta_c \sim 1/q^2A$ (q: safety factor, A: aspect ratio). In the presence of the transport, its achievable β value in marginally stable state is apparently modified from the value obtained by MHD analyses. We here analyze the scaling laws of β_c, using 2D Transport-Equilibrium Code where the enhanced transports are added to the ballooning unstable region. Two different heating-transport scenarios are used; i) $\tau_H >> \tau_c$ and ii) $\tau_H << \tau_c$ (τ_H and τ_c are typical heating time and the confinement time).

For the former case we get

$$\beta_c = 7.88\ q^{-.54}(A-1)^{-.76} \quad (\%)$$

for given current profiles. (Fig.1)

For the latter case, i.e. $\tau_H << \tau_c$, we can heat the plasma untill the second-stable region appears in the plasma column. The remarkable is that in this high-β equilibrium the unstable region merges into stable region by the enhanced diffusion. <u>The ballooning mode does not limit the β value!</u> The figure 2 shows the β = 15% equilibrium stable to ballooning mode.

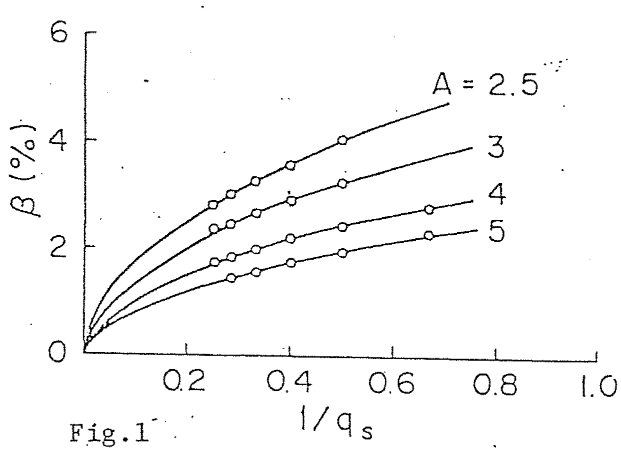

Fig.1

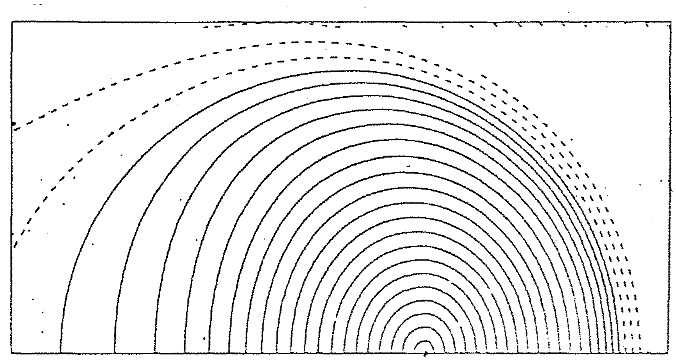

Fig.2

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KINETIC STUDY OF BALLOONING MODE

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Recently, experimental plasma parameters have approached the β limits obtained from MHD analyses. Further application of the MHD theory, however, requires consideration of the kinetic interactions that determine the ballooning stability.

We here investigate the kinetic theory of high-n ballooning mode, examining the effects of finite gyroradius, finite β-value, q-profile, density and temperature inhomogeneities, temperature anisotropy and kinetic parallel conductivity. Starting from the Vlasov-Maxwell equations, general equations for low frequency electromagnetic perturbations in toroidal plasma are derived.

For isotropic plasmas, the MHD ballooning equation is recovered by taking the MHD limit. The lowest order finite gyroradius correction is found to be stabilizing. The stability analysis for anisotropic plasmas shows that an increase of $T_{i\parallel}$ does not cause the ballooning instability. In the kinetic theory, off-resonant instabilities are expected to have smaller growth rates than in MHD and collisionless energy integral theories.

Another important feature of the kinetic ballooning mode is that it is associated with a parallel electric field permitting the wave-particle interactions. The mode belongs to a family of drift-Alfvén modes. We have obtained the eigenmode structure, which has the growth rate of the order of ω_*.

would like adjacent poster - Tuda, Azumi and Kurita.

THE INFLUENCE OF DIFFRACTION ON ERGODIC WAVES*

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A simple model for the study of ergodic wave propagation including diffraction is studied. The model is based on a Schroedinger formulation and reduces to the Chirikov-Taylor map in the zero wavelength limit.[1] The method of paths in Fourier space[2] is applied to calculate the diffusion coefficient. We estimate the role of diffraction in mitigating the effect of accelerator modes.

*Work supported by the Department of Energy.

[1] G. Casati, et al. in Springer Lecture notes in Physics 93; M. V. Berry, et al. Annals of Phys. (1979).
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Trapping in Thermal Barriers

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University of Wisconsin

An important question concerning the viability of thermal barriers in tandem mirrors is the rate at which passing ions become trapped in the barrier. In order to maintain the barrier, the barrier trapped ions must be removed. This work considers some aspects of the barrier trapping problems. The passing ions are treated as collisionless on the transit time scale, so that energy and magnetic moment are constants of the motion, but collisional on longer time scales. The distribution function of passing ions is allowed to be anisotropic in both the barrier and central cell. The pumping of trapped ions in the barrier is treated phenomenologically by the introduction of a pumping coefficient ν, so that the pumping rate is $\nu n_t V_b$, where n_t is the trapped ion density and V_b is the barrier volume. A relationship between the barrier trapping current, barrier potential, and total passing ion density is developed. Using the approximation of a delta function for the anisotropic part of the passing ion distribution function, numerical results are obtained. In addition, a figure of merit (ratio of the end loss current of an unplugged mirror to the trapping current in the barrier) is calculated. It appears that acceptable values for this figure of merit are achieved only at very large central cell-barrier volume ratios, unless hot, magnetically trapped electrons in the barrier are used to increase the barrier potential.

This research was supported in part by DOE under contract ET-79-S-02-5125.

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COMPUTER SIMULATION STUDIES OF THE EFFECT OF HOT ELECTRONS ON THE MHD FLUTE INSTABILITY[+]

by

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The MHD flute instability is initially excited using a 2 1/2 dimensional purely electrostatic code, which is bounded in the x direction and is periodic in the y direction. The driving mechanism of the instability is ∇B drifts associated with the magnetic field $\vec{B} = B(x)\,\hat{z}$ which varies as $1/x$. Here $T_e = T_i$ and $M_i / m_e = 9$.

A part of the electron population is then initialized with a temperature $T_h = 100\ T_e$ and the ratio of hot electron density to total electron density varied to yield different β_h values. For each value of β_h the time evolution of the system is investigated with a 2 1/2 dimensional fully electromagnetic code. Results indicate a stabilization of the flute instability by the hot electron component. Studies are being undertaken to determine β-critical and these results also will be presented.

+ This work is supported by USDOE DE-AM03-76SF00010.

* Plasma Physics Research Institute, University of Natal, Durban, South Africa (also at University of Durban-Westville, Durban, South Africa).

† Supported by CSIR, South Africa.

UCRL-85629

ORBIT-AVERAGED AND IMPLICIT PARTICLE CODES

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ABSTRACT

Significant progress has recently been made in extending the applicability of particle codes to long time scale plasma phenomena . This has been accomplished by means of orbit-averaging and implicit techniques that relax the usual time step constraints required for numerical stability of conventional explicit differencing schemes. The important features of the orbit-averaged implicit methods are substantial reduction of particles, unconditional stability of the field equation(s) solution at large time step, and tailoring and splitting of particle time scales by species and even by velocity class to accurately and efficiently resolve particle trajectories. Some of the more important applications we anticipate are two-dimensional and limited three-dimensional kinetic simulations of equilibrium formation and transport in tandem mirrors with thermal barriers and gun-produced field-reversed mirrors and of low frequency drift waves or MHD instabilities with finite Larmor radius effects naturally included. The new simulation techniques allow use of much more realistic simulation parameters.

We report the successful implementation of new implicit methods and merging of orbit averaging[1] with the moment equation field implicit method independently developed by Mason[2] and Denavit[3] and with the direct implicit particle method due to Langdon, Friedman and Cohen. We have analytically determined rudimentary stability and filtering characteristics and confirmed stable code operation with a linearized electrostatic code and nonlinear one-dimensional electrostatic and two-dimensional magneto-inductive codes. Orbit averaging by itself may lead to numerical instability depending on the underlying physics model. Merging orbit averaging with one of the implicit methods may not give a stable or convergent scheme unless sufficient implicitness is preserved. We will exhibit code results on the simulation of ion acoustic waves and the multiple time-scale simulation of mirror machine build-up, equilibrium and transport.

We have also developed a particular form of the Mason implicit technique[2] in a linearized particle code that accurately reproduces growth rates and real frequencies for ion cyclotron instabilities and low frequency gravity-driven interchange modes with FLR stabilization effects properly calculated. This code allows any value of $\omega_{pi}\Delta t >> 1$.

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*This work was supported by the U.S. Department of Energy under Contract No. W-7405-ENG-48 at Lawrence Livermore National Laboratory and DOE Contract AS03-76SF00034-DE-AT03-76ET53064 at U.C. Berkeley.

POSTER SESSION

ELECTROMAGNETIC DRIFT MODES DRIVEN BY ION PRESSURE GRADIENTS IN TOKAMAK

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The University of Texas at Austin

The electromagnetic formulation of the drift modes is presented to investigate the finite β effect upon the previous low β study[1] of the ion pressure driven drift modes in Tokamaks. The three coupled equations are derived from the hybrid of hydrodynamic equations and of the kinetic equations; the cross field current from the former and the parallel current from the latter. The compressional component equation of Ampere's law represents the pressure fluctuation balance and it is utilized to reduce the mode equations to two coupled equation for electrostatic (e.s.) field ϕ and electromagnetic (e.m.) field ψ. From the local approximation, the dispersion relation of the fifth order is derived and the resulting modes are characterized by their polarization characteristics $\alpha=\psi/\phi$, as e.s. ($|\alpha|<<1$), e.m. like ($|\alpha|>>1$) and MHD-like ($\alpha\simeq1$). The results of the numerical solutions in the various β-regimes are discussed.

[1] D-I. Choi, W.M. Tang, and Wendell Horton, FRCR #204 (to be published in Phys. Fluids, 1981).

This work is supported by DOE Contract No. DE-AC05-76ET 53036 and Grant No. DE-FG05-80ET 53088.

Destruction of Adiabatic Invariance*

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A Hamiltonian formulation[1,2] of the theory of adiabatic invariance is described. The formalism is illustrated by constructing to second order the adiabatic invariant of a harmonic oscillator with slowly varying frequency. The method is then employed to study charged particle motion in electromagnetic fields weakly inhomogeneous in space and time, and to analyze the destruction of the adiabatic invariants μ and J in various situations of interest. Non-canonical variables are used to prepare the Hamiltonian in the form $H = H_o + \varepsilon H_1 + \ldots$ where ε is the small ratio of gyroradius to scale length or bounce frequency Ω_b to gyrofrequency Ω_c and H_o is independent of both gyration phase and bounce phase. Near identity symplectic (Lie) transformations are then constructed to remove angle dependence from H, thereby constructing the adiabatic invariants. Resonant denominators of the form $\ell\Omega_c + m\Omega_b$ signal destruction of μ and J in certain regions of phase space. General expressions for the approximate extent of the stochastic regions are constructed and employed in the special case of a trapped particle in axisymmetric tokamak geometry. Extensions to more realistic magnetic fields are indicated. General questions relating to the theory of adiabatic invariants and symplectic dynamics are also discussed.

* This work was supported by United States Department of Energy Cotract No. DE-AC02-76-CH03073.

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[2]R. G. Littlejohn, La Jolla Institute Report No. TJN-81-113 (1981).

Poster Session

Abstract Submitted
for the 1981 Sherwood Meeting

Annual Controlled Fusion Theory Conference
Austin, Texas
April 8-10, 1981

Numerical Simulation of Burning Plasmas in Compact Toroids. R. N. BYRNE, W. GROSSMANN*. A 1-1/2 D equilibrium and transport simulation code capable of long time evolution studies of FRC and more general CT plasmas has been developed and reported on earlier [1]. More recently reaction kinetics have been added to the code allowing simulation of a burning CT plasma. We have used the code for a study of D-T burns typical of those considered for the moving ring FRM reactor concept[2]. We find 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 with a slit developing from the o-point as the elongation increases. Another feature of these burning plasmas is the persistence of current on the magnetic axis or slit. Usually transport tends to flatten the pressure profile there, and the current and field both vanish as a result leaving only the edge of the plasma to carry a current and support a pressure gradient. This does not happen in the present case, at least not on the same time scale, for the burn deposits energy at a rate sufficient to maintain the toroidal current.

*Present address New York University.

(1) R. N. Byrne, W. Grossmann, Proceedings of Third Symposium on Physics and Technology of Compact Toroids, Dec. 2-4, 1980, LASL, Los Alamos, N.M.
(2) A. C. Smith, et al., ibid.

Work partially supported by U.S. DOE, Contract No. DE-AC02-76ER03077 and EPRI Contract RP922.

(x) Prefer Poster Session
( ) Prefer Standard Session
( ) No preference

Signature of APS Member

R. N. Byrne
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1981 Sherwood Meeting

MODEL OF ANOMALOUS RESISTIVITY IN TWO-DIMENSIONAL MHD CALCULATION OF FIELD-REVERSED THETA PINCHES

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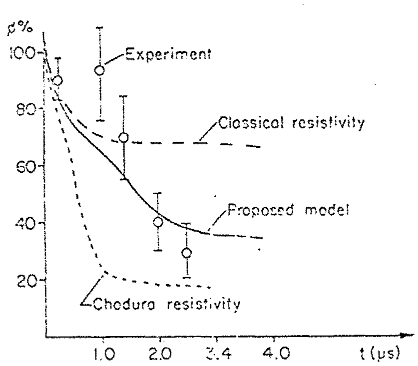
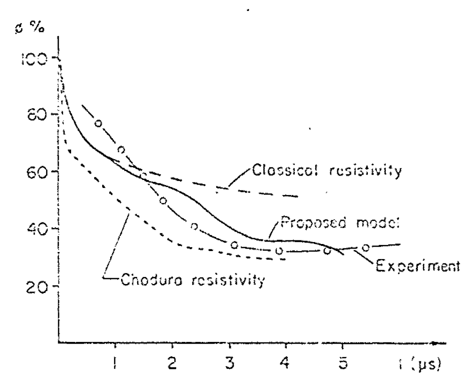
ABSTRACT

In field-reversed theta-pinch experiments an important parameter determining the final plasma conditions is the amount of magnetic flux trapped in the plasma. It has been shown that trapped flux influences not only the plasma diameter but also the axial plasma compression. Since in low density plasmas anomalous effects dominate plasma resistivity, these effects must be included. In current 2-D MHD calculations of field-reversed pinches, Chodura resistivity followed by lower hybrid resistivity or increased classical resistivity are used. Both approaches predict final plasma parameters, including the amount of magnetic flux trapped in the plasma, in good agreement with experiments, but flux is lost much faster with these models than in the experiments. The reason for this discrepancy is that these models assume resistivity as a function of local parameters only. Anomalous resistivity as a result of micro-instability is certainly a function of time until it reaches the saturation level. The model presented in this paper includes this effect, allowing resistivity to grow from a classical level. The growth rate of resistivity is assumed to follow the growth rate of the lower hybrid instability. It is also assumed that it cannot saturate before complete field line reconnection. (The Saturation level increases by 10^6 times in the computer model before full reconnection.) As one can see from available experimental data, the calculation follows experiments quite well both for the FRX-B experiment, where field lines reconnect at ~1.8 μs, and for HBQ, where no reconnection has been observed. This model should be considered semi-empirical but it offers improvements over previous models.

This work was supported by DOE-MFE.



FRX-B experiment



HBQ experiment

Magnetic flux in plasma as a function of time

UCRL-85660

MICROSTABLE SLOSHING ION MIRROR PLASMA?

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ABSTRACT

The ion distribution in a mirror-confined plasma is generally unstable to the DCLC mode because of the ambipolar hole in velocity space. It has been shown by Ioffe, et al.[1] that the plasma can be stabilized by cold ions trapped in a potential dip near the midplane. In Ioffe's experiment this was produced by anisotropic heating of the electrons. This potential dip can also be created by energetic neutral beam injection at some acute angle with respect to the magnetic field direction. The result is a "sloshing" ion distribution for which the hot ion density and the potential have a local minimum at the midplane.[2] A residual low level of RF fluctuations[3] is necessary to push ions to the bottom of the potential well from the bulk ion distribution or from an auxiliary source of low energy ions; e.g., neutral beams injected normal to the magnetic field at the midplane. We have calculated ion distribution functions for this situation using a bounce-average Fokker-Planck code, supplemented by terms representing quasi-linear RF diffusion and neutral beam sources. Results are analyzed for microstability using simple analytic theory. A parameter survey is in progress.

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POSTER SESSION

Equilibrium of Diffuse Minimum-B Mirrors*

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Analytic three-dimensional mirror equilibria have been calculated from the tensor-pressure fluid equations by means of an asymptotic expansion procedure. We expand the equations in the small-mirror-ratio limit by ordering the magnitudes Δ_B and Δ_E of the bumpy and elliptical fields and the plasma $\beta = 2P/B^2$ in terms of $\delta = R_m - 1$, where R_m is the mirror ratio on axis. The result is a simplified set of MHD equations, which are closed by applying the lowest-order parallel current constraint. The constraint determines the function $\psi(r,\theta)$ which specifies the radial variation of the pressure, $P_{\perp,\parallel}(\psi,B) = P(\psi)g_{\perp,\parallel}(B)$, including self-consistently the effect of the plasma diamagnetism.

The class of equilibria described here are relevant to the minimum-B end cells of present tandem mirror experiments. We make use of this equilibrium solution to obtain an analytic estimate of the critical beta for interchange instability due to the diamagnetic modification of the vacuum magnetic well.

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Absorption of Kink-like Modes at the Alfvén Resonance in Current Carrying Low-β Plasmas

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From recent investigations into Alfvén wave heating {1,2,3} it is known that efficient coupling between an antenna and shear Alfvén waves may be achieved when a kink-like mode is excited first. Theories, in which the equilibrium current is neglected but the shear is retained, predict satisfactory coupling from helical antennae only to resonant surfaces near the plasma edge {3,4,5}. In contrast to this we have predicted good coupling to inner surfaces on the basis of an ideal MHD-model in which the equilibrium current has been retained {2}.

Using the same MHD-model in cylindrical geometry both with and without an equilibrium current, we are able to explain the abovementioned discrepancy. The kink-motion is highly sensitive to the equilibrium plasma current; it is therefore plausible that the coupling from the antenna to the shear Alfvén wave depends also on the equilibrium current. In an application of the cylindrical and a toroidal MHD-model to the Lausanne Tokamak TCA we demonstrate the practical importance of this result.

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Ideal MHD Stability of the EBT Configuration

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An analytic theory is presented of the ideal MHD stability properties of the EBT configuration. The theory makes use of the rigid ring assumption as suggested by Nelson and Hedrick. By assuming the mirror ratio is small (i.e., $B_{max}/B_{min} - 1 \sim \delta << 1$), it is possible to obtain explicit analytic expressions for the interchange and ballooning mode stability criteria. Perhaps the most interesting result is the fact that a small ring pressure, $\beta_e \sim \delta^2$, can completely stabilize the EBT configuration for finite values of the plasma pressure, $\beta \sim 1$. The results appear to be in good agreement with numerical computations carried out at Oak Ridge even though the theory is used outside its strict region of stability.

VAX Computer Performance for Particle Simulation

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The CRAY-I computer is geared to have very fast execution times and it may not be suitable for simulations requiring extremely large memories. On the other hand, the VAX 11/780 (at UT and UA) equipped with a 300M byte disc memory handles up to 8M words. Such a large memory size can considerably increase the ratio of the spatial length to the collisionless skin depth for the particle simulation code.[1] The VAX computer, however, has a much smaller fast memory and the working set size is further limited. The VAX operating system automatically maps out the large dimensions from the relatively small working set to the disc through paging: the programmer does not have to be concerned rigidly about the memory size. It, however, becomes critical when dimensions become very large, because the computer spends most of the time in paging.

We have investigated the dependence of the execution time for various components of the particle code as a function of the grid size. We have carried out this investigation for various values of the assigned maximum working set size. When the grid size reaches a certain limit, the execution time jumps up because of much paging. We also found that this critical grid size is greatly enhanced as the allowed working set size is increased. This suggests that even though the paging handles the large mapping automatically, the cost effective (faster) computation may be achieved by a code calling in a segmented grid and particles.

*This work supported by DOE Grant, DE-FG05-80ET 53088.

[1] J.N. Leboeuf, K. Whang, T. Tajima, and M. Makino, to be published in Proc. of the Fourth Topical Conf. of the RF Heating Plas., where four times as large memory as the CRAY-I can take, was needed, and the run was executed on Nakoya IPP's M200. The UT VAX 11/780 could also hold as large a grid as done on M200 with much paging.

POSTER SESSION

FIELD LINE GEOMETRY FOR ERGODIC MAGNETIC LIMITERS*

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ABSTRACT

An ergodic magnetic limiter (EML) configuration[1,2] can be established on an axisymmetric tokamak plasma equilibrium by imposing an external nonaxisymmetric magnetic field. The external field should have helical components which create overlapping islands near the plasma boundary; these components should fall rapidly to zero in the plasma interior so that the plasma core is undisturbed. Here we use a simple equilibrium model and assess the feasibility of creating EML configurations with $q = 3$ at the plasma boundary and with $q = 2$ at the plasma boundary. Promising configurations are identified using the Fourier analysis technique described in the last poster. Field line tracing calculations are performed to determine the extent of ergodic regions and island widths for a variety of helicities and q values. Comparisons are made between these field line tracing results and estimates, based upon a combination of analytic formulas and the Fourier analysis information.

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*Work supported by the Department of Energy, Contract DE-AT03-76ET51011.

High-n Kinetic Ballooning Modes in Tokamaks*

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Employing the high n ballooning mode and WKB formalism, a second order differential equation describing kinetic ballooning modes has been derived in the frequency regime, ω_{bi}, $\omega_{ti} < \omega < \omega_{be}$, ω_{te}. Compressional effects due to perpendicular magnetic vector potential $A_\perp$, trapped electrons, ion magnetic drift resonance and Larmor radius effects are retained. No assumptions are made on β and $k_\perp\rho_i$, but magnetic drift frequencies are taken to be of the same order as ω. The main driving term is associated with the circulating electron magnetic drifts. The equation is then applied to a model equilibrium employed in the previous MHD calculations.[1] If the trapped electrons are neglected, we first show that in the limit, $k_\perp\rho_i << 1$ and $\omega_{di}/\omega << 1$, the kinetic equation corresponds to the ideal MHD ballooning mode equation. For arbitrary $k_\perp\rho_i$ and $\omega_{di}/\omega \sim 0$ (1), we find that the unstable region is broader than in the ideal case [$\beta_{c1} < \beta_{c1}$(ideal) and $\beta_{c2} > \beta_{c2}$(ideal)], except when $\eta_i = 0$ ($\eta_i = d\ell nTi/d\ell nN$) they are identical. The growth rate is smaller than the ideal growth rate due to finite ion Larmor radius and magnetic drift effects. For $\eta_i = 0$ the kinetic effects do not modify the stability boundaries because at marginal stability with $\omega = \omega_{*i}$, the ions behave adiabatically so that the ideal MHD assumption $\underline{E} + \underline{V} \times \underline{B}/c = 0$ is satisfied except due to ion diamagnetic drift effects.

Including trapped electrons, the unstable region shifts toward higher β and trapped electrons effects are stabilizing. Finally, the solutions of the kinetic ballooning mode equation have been compared with the results of a more general code developed by Rewoldt et al.,[3] and the agreement is excellent with difference of less than 1% when $\omega_{ti} < \omega < \omega_{be}$ is satisfied.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

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TWO-FREQUENCY FERMI MAP*

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For a collisionless plasma, ECRH is thought to be limited by the existence of isolating KAM curves at higher velocities. It has been suggested that it may be possible to raise the adiabatic barrier by heating at two closely spaced frequencies. In order to investigate the feasibility of this scheme, we model the ECRH problem with the normalized symmetric two-frequency Fermi sine map,

$$u_{n+1} = \left| u_n + \frac{\sin s\phi_n + \varepsilon \sin r\phi_n}{\sqrt{1+\varepsilon^2}} \right|$$

$$\phi_{n+1} = \phi_n + \frac{4\pi M}{(r+s)u_{n+1}} ,$$

where r and s are coprime integers and ε is the amplitude ratio ($0<\varepsilon<\infty$). Fixed points are located and found to bifurcate as ε increases. Analytic local linear stability criteria and bifurcation thresholds are derived and confirmed numerically. Global stability limits are derived analytically for $\varepsilon=0$ and ∞, and determined numerically in the interesting case of comparable amplitudes ($\varepsilon \simeq 1$). The results show considerable destruction of local stability but only a modest increase in the KAM barrier.

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INVARIANT PROBABILITY DISTRIBUTION ON A STRANGE ATTRACTOR*

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ABSTRACT

Recently we have developed an analytical method for the calculation of statistical properties of Chirikov-Taylor model.[1,2] This method involves the presentation of temporal evolution of the Fourier amplitudes of the distribution function as paths in a Fourier space. The main utility of the method is that it is only selected paths which contribute in the limit of long times. In the present paper we apply this method to a model which exhibits strange attractor type solutions. The analytic expressions for the invariant probability distribution and Lyapunor characteristic exponent has been derived. These results will be compared with numerical computations.

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ENHANCEMENT OF CLASSICAL AND NEO-CLASSICAL DIFFUSION BY NARROW BAND TURBULENCE

by

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Experimental measurements of transport rates, particles and energy have often shown that the rate is close to the value predicted by the classical theory, but is larger by a small factor. Experiments with internal conductor systems for particle transport and experiments with tokamaks for energy transport through the ion channel are examples. In both cases, the plasmas are grossly stable, but the fluctuations in densities and temperature are observed. In this paper, a model is presented to explain the observation.

The diffusion across the magnetic field occurs because the charged particles have finite orbit sizes perpendicular to the magnetic field. The orbit is interrupted either by binary collisions, in cases of classical and neo-classical diffusion, or by loss of correlation in case of turbulent diffusion. Here we consider the in-between case where the correlation time is much longer than the binary collision time. The idea is that the amplitude of the perturbed orbit depends on the relative size of the wave length and the unperturbed orbit size, and the stochasticity is provided by the binary collisions. The calculations show that both the classical and the neo-classical transport rates are enhanced by the effects.

COMPUTER SIMULATION OF NON-LINEAR ION–ELECTRON INSTABILITY

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Numerical experiments with a one-dimensional ion-electron self-consistent electrostatic plasma in the presence of a electron drift v_d are presented. A self-sustaining state of phase space density granulations or "clumps"[1,2] can exist when the decay of these fluctuations due to ballistic streaming and turbulent electric fields is balanced by the creation of new ones through the mixing of average gradients. Over-regeneration implies that the system will be unstable.

We report the onset of instability for electron drifts well below the threshold of linear instability for an equal temperature plasma. This nonlinear instability appears to be due to the regeneration of electron and ion clumps[3]. We perform detailed phase space diagnostics and measure integrals of the two-point correlation function to determine the structure and time behavior of the clumps. The instability growth time depends on the fluctuation level and is of the order of the trapping time $(k^2D)^{-\frac{1}{3}}$. Here k is a typical wave number and D is the velocity space diffusion coefficient. The fact that the stability threshold is significantly lower than the linear boundary and that similiar phenomena should occur in more complex geometries has obvious ramifications for confinement and transport theory.

This work is supported by the National Science Foundation and the Department of Energy.

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Stability Studies of Compact Toroids

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ABSTRACT

We present recent results from studies of ideal MHD and guiding center fluid (GCF) stability analyses of compact toroids. The MHD studies use the long-thin approximation to model FRC plasmas. Preliminary results showing FRC configurations stable to transverse MHD (incompressible) modes have been presented elsewhere.[1] We present here more complete and definitive results of stable configurations for several equilibria both of which are reasonable models of an FRC plasma exhibiting a flatness in the pressure profile in both the radial and axial directions. We mention at the outset that both equilibria are unstable to longitudinal modes (compressible) in ideal MHD, consequently our equilibria are necessarily unstable to a full MHD stability analysis. Our motivation for examining the transverse modes comes from experimental observations obtained on the LASL FRX device which seems to indicate stability to motions perpendicular to the magnetic field and toroidal axis.

More recently a study of general axi-symmetric equilibria in the GCF model has led to a series of new results concerning the stability of compact toroids. For general configurations a sufficient condition for stability can be given in terms of 6 ODE's on each field line in a manner similar to that of ideal MHD.[2] Moreover, a sufficient condition for instability is $\partial S/\partial B \leq 0$ on a field line where $S(\psi,B)=P_{\parallel} B^5/P_{\perp}{}^3$. Specializing to an axi-symmetric CT shows the sufficient condition for stability also to be necessary if $\partial S/\partial B \equiv 0$. In this case the condition reduces to a single second order ODE on each field line. Essentially the same second order ODE yields a sufficient condition for stability if $\partial S/\partial B \geq 0$. The differences between parallel and perpendicular pressures can have a strong stability effect and simple configurations (z-pinch) which are unstable in MHD may be easily stabilized.

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Poster Session

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ALPHA PARTICLE LOSS AND ENERGY DEPOSITION IN TANDEM MIRRORS

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Alpha particles from fusion events in the central cell of a tandem mirror primarily slow down on electrons until their energy is low enough for angle scattering off ions to be competitive. Some alphas then scatter out through the magnetic mirror loss cone, until the alpha energy is less than $2e\phi_c$, the plug confining potential. Analytical and numerical investigations of the loss of alpha particles and the deposition of their energy will be presented.

The drift kinetic equation for a tandem mirror is bounce-averaged, giving a separable differential equation in $E \equiv v^2/2$ and $\lambda \equiv \mu B_{min}/E \equiv v_\perp^2 B_{min}/v^2 B$. The E dependence is analytically tractable, only requiring the numerical evaluation of well-behaved integrals. The λ dependence generally requires numerical solution, although some analytical progress can be made. Taking moments of the drift kinetic equation and flux surface averaging then give particle loss and energy deposition rates.

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Numerical Studies of Toroidal Resistive Instabilities*

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We have constructed a time-stepping code to study the dominant resistive MHD instability of an axisymmetric toroidal plasma. The model used is based on the linearized, incompressible MHD equations with constant resistivity and density. The equations are solved implicitly using a modified PEST coordinate system for which one of the coordinate surfaces coincides with surfaces of constant poloidal flux. This is crucial for the accurate numerical representation of modes for which the perturbed quantities vary rapidly near rational q-surfaces. Results are presented, and also comparisons with a cylindrical resistive code and with a toroidal ideal MHD code (PEST).

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POSTER SESSION

POSTER SESSION

EFFECT OF ELONGATION ON THE STABILITY OF DRIFT WAVES*

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ABSTRACT

A study of the effect of elongation on the stability of drift waves in a sheared magnetic field is presented. The cold-ion fluid equations in an elliptical cylinder are analyzed using a ballooning mode formalism. The ellipticity (characterized by an elongation parameter κ) causes the modes to be of two types: prolate and oblate. A condition on κ which is sufficient to overcome shear stabilization is found: $\kappa^2 > 1 + \hat{s}^2$, where $\hat{s} = r\, d\, \ell n\, q/dr$ is the shear strength parameter. Mode stability due to this effect and its implications for realistic tokamak parameter regimes is discussed. The analysis is extended to the kinetic drift wave equations.

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UCRL-85642

NUMERICAL SIMULATION OF TMX OPERATION

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ABSTRACT

The buildup and quasi-steady state phases of operation of the tandem mirror experiment (TMX) at Lawrence Livermore National Laboratory have been simulated using a one-dimensional radial transport code (TAMBAR) which dynamically models plasma behavior in both the central cell and end plugs of the machine. The fluid model which is used in TAMBAR incorporates classical radial transport, three-dimensional cold gas transport in cylindrical and/or slab geometry, and neutral beam transport corrected for finite-Larmor-orbit effects in both the central cell and end plugs. In addition, degradation of plug and central cell confinement and bulk heating of central cell ions due to end plug RF fluctuations are treated using analytical models based upon the numerical work of Rognlien and Matsuda[1].

Depending upon the RF model used and upon the mixture of direct central cell to end-fan region gas fueling which is assumed, agreement between the simulations and TMX data can be as good as 30% for on axis densities. The significance of this agreement between the physical model used in the code and the experiment and the significance of some of the more notable discrepancies between the code results and experimental data are discussed in terms of how they relate to current understanding of gas fueling and confinement in TMX.

*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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ANOMOLOUS TRANSPORT EFFECTS ON ELECTRON HEATING BY A FINITE SPECTRUM OF LOWER HYBRID WAVES*

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A 2-D code (plasma radius r, and electron speed v) has been recently developed which models the combined effects on electron transport of a stochastic magnetic field and a radial ambipolar electric field. Combined with collisions, Ohmic heating and RF heating, we have

$$\partial f_e/\partial t = C(f_e) + H + 1/v^2 \partial/\partial v\, v^2 D_{QL}(\partial/\partial v\, fe) + 1/rv\, \mathcal{L}\, rv^2\, D(v,r)\, \mathcal{L}\, fe$$

where $\mathcal{L} = (\partial/\partial r - e\, E_r/mv\, \partial/\partial v)$, E_r is the radial electric field, D(r,v) is an effective length given approximately by the autocorrelation length of an electron in the stochastic field times the normalized mean square fluctuation in amplitude, H is a Spitzer-Harm heating term and C(fe) is a 1-D Fokker-Planck treatment of the collisions. $D_{QL}(v,r)$ is a lower hybrid heating diffusion coefficient used to describe the effects of an applied RF field. The above equation is coupled to an equation which solves for the radial penetration of the RF energy. The lower hybrid waves are assumed to be excited from a finite length antenna. An RF electric field power spectrum is assumed at the boundary r = a allowing for the calculation of D_{QL} throughout the plasma through the solution of the equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\, \mathcal{E}(v,r)\, \frac{\partial}{\partial \omega}(\omega\varepsilon)\, v_{gx}\, \frac{\omega}{v^2}\, dv\right) = P_{RF}(v,r)$$

where $\mathcal{E}$ is the electric field power spectrum, v_{gx} is the perpendicular group velocity, $P_{RF}(v,r)$ is the RF power per unit volume in the velocity space increment dV and

$$D_{QL}(v,r) = 8\pi^2\, \frac{e^2}{m^2}\, \frac{1}{v}\, \mathcal{E}(v,r)\, \frac{1}{(1 + k_\perp^2/k_\parallel^2)} \quad .$$

Parameter studies are done for various values of $n_\parallel = c/_{vph_o}$ and spectral width. Here vph_o is the central phase velocity. We examine electron heating efficiencies and RF energy penetration.

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Would prefer Poster Session.

THEORY OF ION COMPTON SCATTERING FOR DRIFT WAVE TURBULENCE IN A SHEARED MAGNETIC FIELD

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A theory of ion compton scattering for drift wave turbulence in a cylinder with shear is presented. A renormalized gyrokinetic equation is derived and (for low turbulence levels) is solved iteratively to construct the turbulent ion response. Noting that the region within the Pearlstein-Berk turning points is most important to eigenmode stability, the eigenmode equation is solved and the nonlinear damping rate is obtained. Compton scattering is the physical process underlying this damping.

The result is applied to the regime where stochastic electron motion destabilizes the driftwave.[1] A saturation criterion equation is derived by balancing the nonlinear damping rate with turbulent electron growth and linear shear damping. This equation constitutes an integral equation for the mode spectrum. The Compton scattering process results in a transfer of spectrum energy to long wavelength. Thus, solution of the saturation condition equation predicts that for $k_\theta \rho_s = 1$, ω_c/ω (ω_c is the electron decorrelation rate[1]) can be substantially less than unity. Radical changes in parameter scaling are also found. Indeed, one can raise the question of whether or not fluctuation levels consistent with destabilization by turbulent electron growth are ever achieved! Thus, it is argued that ion nonlinearity must be considered in constructing a theory of anomalous electron heat transport due to drift wave turbulence.

This work is supported by DOE Grant DE-FG05-80ET 53088.

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Effects of Nuclear Elastic Scattering on Advanced Fuel Burns

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At the high operating temperatures required for advanced-fuel burns the probability of Nuclear Elastic Scattering (NES) for fusion products (fP) becomes significant[1,2]. These large energy-transfer events have the effect of depositing the fusion product in an energy range more favorable for energy transfer to ions, thus increasing the fraction of the fusion energy imparted to the plasma ions. Also associated with these NES reactions is the creation of a population of high energy knock-on ions which increase the average fusion reactivity. Another consequence of NES is a reduction of the slowing down time of the fusion products and a corresponding lowering of the superthermal particle pressure.

The purpose of this study is to investigate the effect of NES on overall plasma characteristics, such as $n\tau_{ignition}$ and power density for D-based fuel cycles.

Slowing down of fusion-products is modeled using the multi-group form of the Boltzmann equation[1]. In this form the discrete large energy transfer in NES events can be accounted for directly. This equation is solved for the steady-state superthermal particle (i.e., fP and knock-on) distributions providing, among other things, the fraction of the fP energy imparted to the plasma ions and electrons and the superthermal particle pressure. This information may be used to solve the steady-state ion and electron power balance for $n\tau_{ignition}(T)$ and fusion power density.

As an example of the effects of NES consider a 14.7 MeV proton slowing down on a deuterium plasma (T_i = 100 KeV, T_e = 75 KeV). With NES, the fraction of the fP energy going to ions is increased by 15%, the slowing down time reduced by 30%, and the steady-state superthermal particle pressure reduced by 10%. These effects reduce the requirements for $n\tau_{ignition}(T)$ and increase the fusion power density for a specific β, $\vec{B}$-field and ion temperature.

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EFFECT OF PLASMA CURRENT ON RESTORING FORCE IN TOROIDAL-HELICAL CONFIGURATION

by

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In current carrying toroidal-helical MHD equilibria, the toroidal displacement of a plasma column in an $\ell = 2$ helical magnetic fields produces an effective vertical field which acts as a restoring force against the expansion of plasma loop.(1) If the plasma current is strong, it may modify the magnetic field in two ways. First the toroidal plasma current introduces poloidal field, which although neglected in the usual stellarator theory, is particularly important for high current configurations such an OHTE (2) and may even produce observable effects in ohmically heated stellarators. Second, the helical shape of the plasma generates an effective helically symmetric current which modifies the helical magnetic field(3). The effective vertical field $B_\perp$ produced by the toroidal shift δ of plasma with major radius R for arbitrary poloidal field including the effect of helical plasma current has been derived by using an averaging method. If the second order toroidal effect is neglected, the toroidal-helical coupling (sidebands) effect also disappears in the averaging process. In the weak plasma current regime for an $\ell = 2$ stellarator it is expressed in the form

$$B_\perp = \frac{\delta}{R} B_o \iota\!\!\!-_o \left(1 + \frac{2}{3nq_o}\right) \Big/ \left(1 + \gamma\right)^2 , \tag{1}$$

where B_o, $\iota\!\!\!-_o$, n and q_o are the toroidal field, rotational transform of vacuum helical field, toroidal period number and safety factor of Ohmic current. The effect of helical plasma current is included in $\gamma \simeq 1/nq_o$. In the limit $q_o \to \infty$, Eq (1) reduces to Yoshikawa's formula (1). The result (1) will be compared with JIPPT-II Stellarator experimental data.

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Collisionless Reconnection With Parallel Electron Drift*

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We analyze the linear stability of collisionless reconnecting modes in finite-β plasmas. A sheared field configuration is considered, as well as all the effects of a non-uniform electron drift velocity along the magnetic field.(1) This leads to an asymmetric singular layer solution. The asymmetric part of the solution affects the eigenvalue of the problem (the mode frequency and growth rate) to the extent that the radial amplitude of the perturbed magnetic field has a significant variation within the singular layer.

Adiabatic ion response in the singular layer reduces the resulting integro-differential equation to a pair of second-order differential equations.

Numerical solutions are obtained using invariant imbedding(2) techniques to avoid inherent instabilities in the solution.

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THE RIPPLING MODE

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The linear theory of the rippling mode is examined. The theory of this mode, as formulated by Furth, Killeen, and Rosenbluth[1], is extended to include the effects of: (a) parallel electron thermal conduction,[2] (b) parallel pressure perturbations in Ohm's Law, and (c) finite pressure gradient and ω_* (the diamagnetic frequency). The effects (a) and (b) are shown to enter in the same order, while effect (c) may enter as an independent parameter. The different frequencies and growth rates of this mode in different regions of the parameter space defined by β, the plasma beta, S, the magnetic Reynolds number, and $k_\perp$, the perpendicular wavelength, are presented. The relation of this mode to the temperature gradient-localized drift wave,[3] and to the nonuniform-current driven collisionless drift wave[4] is established. Practical implications of the rippling mode are discussed.

*Work supported by the Department of Energy.

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THE KINETIC THEORY OF BALLOONING MODES FOR MULTIPOLES*

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To account for the apparent large discrepancy between stable high beta plasmas observed experimentally in multipoles and the ballooning mode beta limit calculated from ideal MHD theory we study a kinetic theory approach to the problem of ballooning modes. The collisionless stability theory of low frequency, $\omega \ll \Omega_{ci}$, electromagnetic modes is formulated for axisymmetric shearless magnetic configurations such as the multipole. Perturbed quantities are derived from the linear Vlasov equation assuming the Larmor radius is small compared to equilibrium scale lengths. These quantities are used with the quasi neutrality condition and the perturbed momentum balance equation to obtain a set of integro-differential equations governing the modes. The equations include finite Larmor radius effects, trapped particle and untrapped particle effects and wave particle resonances.

For the low frequency regime, $\omega \ll \omega_{bi}$ and small ion Larmor radius an additional expansion gives a more tractable form of the above equations. These equations are solved for the Levitated Octupole using self consistent equilibria. Criteria for the occurrence of ballooning modes are given and a three dimensional representation of the mode is calculated. Results indicate retaining terms involving the diamagnetic drift frequency has a significant stabilizing effect on on the modes. Trapped and untrapped particle effects force the radial extent of the mode to go to zero at the separatrix.

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Numerical Investigation on Sawtooth Oscillations in Tokamak NBI Experiments

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A simple model is established for the rising phase of sawtooth oscillation and internal disruption in order to simulate whole sawtooth oscillations in tokamaks by using a tokamak one dimensional transport code. Following Jahns et al's work[1], we calculate the island width of m=1/n=1 tearing instability in the Joule heating phase; $W=W_0 \exp\int^t \gamma dt$, where W_0 is its initial value and γ is the linear growth rate for m=1/n=1 tearing mode including diamagnetic frequencies[2]. When the island width W reaches the singular surface $r_s(q(r_s)=1)$, the internal disruption occurs and we change electron density and temperature and plasma current density according to Kadomtsev's theory[3].

Applying this code, we investigated numerically characteristics of sawtooth oscillations observed from NBI experiments on JFT-2 tokamak at JAERI with q_a=3.2, R/a=3.6 and NBI of 1 MW and 34 keV (co+counter injections). Periods of the sawtooth oscillation are obtained to be 1∿1.5 msec without NBI and 2∿5 msec with NBI and its maximum amplitude is 320 eV, which are consistent with the experiments. It is found, however, that the period and amplitude depend strongly on electron loss and disruption model. The detail of the calculation and the comparison with results based on Dnestrovskii et al's[4] will be presented.

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UCRL-85639

ION CYCLOTRON RESONANCES AT HIGH ENERGY IN 2XIIB**

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ABSTRACT

A monochromatic ion-cyclotron wave was observed in 2XIIB to induce very fast diffusion, in velocity space, of the injected ions towards both low and high energies. Diffusion at low energies has been explained (Smith, et al.) as stochastic behavior, due to the overlap of resonances between the wave and the particle's cyclotron, azimuthal drift and bounce frequencies. However, this mechanism fails to explain diffusion at high energy ($W_\perp \sim$ 20-40 keV).

We study here the motion of ions with arbitrary Larmor radius, in a shallow quadratic magnetic well, in cylindrical geometry. It is then shown that a second set of resonances (at $\omega_D \sim \Omega_C$) can exist at these energies, for axis-encircling particles with guiding-center radius of the order of the Larmor radius. The observed wave potential is enough to induce 2-D trapping, where the radial E x B drift strongly modifies the behavior of resonant particles and increases the island width. Island overlapping can then occur and explain the observed diffusion.

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*Participating Guest on leave from Centre d'Etudes Nucleaires, Fontenay aux Roses, FRANCE.

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POSTER SESSION

PLASMA OPERATION CONTOURS FOR THE FED*

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A method has been developed for combining the information generated from a series of 1-1/2-D time-dependent transport code simulations into a set of Plasma Operation Contour (POPCON) plots in density-temperature space. Near-thermal equilibrium conditions can be generated over a wide range of densities and temperatures by using feedback on the amplitudes of the particle and energy sources and stretching out the time evolution over many confinement times. Contours of near equilibrium supplementary heating power, fusion power output, plasma beta, and Q are then used to provide guidance for determining the potential operating regime for the plasma, the relationship between ignited and driven operation, and optimal startup sequences for supplementary heating for a given set of physics models. The impact of variations in the physics models and other parameters is easily demonstrated through comparison of contours from separate runs. The effects of including the Shafranov shift on neutral beam penetration and ripple ion conduction losses, variations in the electron and ion thermal conduction models, neutral beam injection energies in the range 100-400 keV, and an idealized gaussian heating source have all been examined to date. The advantages of a ramped density startup for neutral beam heating is illustrated by the presence of a saddle point in supplementary power requirements. A summary of the results of these studies will be presented.

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1C42

Kinetic Effects on the Toroidal Ion Temperature Gradient Drift Mode

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The question of the threshold of the ion temperature gradient drift mode in toroidal geometry is examined from the drift kinetic equation, retaining the grad-B and curvature drift resonances of the ions with the mode. The transcendental mode equation is solved approximately, and the stability of the resulting modes is analyzed in terms of the Nyquist diagram method. Analytic criteria for the onset of the instability are derived which exhibit a parametric dependence on toroidicity, temperature gradient and perpendicular wavenumber. Analytic results for growth rates and marginal stability are compared to numerical solutions which include correction for finite gyroradius. The applicability of the results to a plasma with a high energy ion component is discussed.

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BIFURCATIONS OF PERIODIC ORBITS AND OF CHAOTIC ATTRACTORS IN THE THREE WAVE PROBLEM

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ABSTRACT

We present results of a detailed numerical study of the "three wave problem"[1] in the nondegenerate case ($\gamma_2 \neq \gamma_3$: unequal damping rates for the two daughter waves). A number of different dynamical behaviors are observed as the parameters of the system are varied. Period doubling and period halfing occur as a parameter is varied monotonically. Tangent bifurcations from chaos to the stable fixed point occur, exhibiting intermittency. Finally, we report the occurrence of drastic changes in the chaotic attractor itself: "chaotic attractor bifurcations." The simplest chaotic attractor manifests itself as an arc in the Poincaré section. As a parameter is varied, the size of this arc increases, reaches some critical size and a new arc is generated, disjoint from the first one. This process may repeat itself. We analyze this type of bifurcation using one dimensional maps.

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SAFETY FACTOR PROFILE OPTIMIZATION OF HIGH n IDEAL BALLOONING MODE STABILITY OF TOKAMAKS*

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Improved stability conditions to high-n ideal MHD modes are obtained with equilibria generated by flattening and raising the q-profile. Flat q profiles shorten the connection length for high-n ballooning modes and diminish the destabilizing impact of the geodesic curvature. High values of q stabilize the residual interchange modes.

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POSTER SESSION

Computer Simulation of Generalized Adiabatic Reversed Field Mirror

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ABSTRACT

A code for simulating a three region periodic mirror with a "loop" field reversal has been constructed. The separatrix is a loop with an x-point between the island and the axis. The problem solved is "generalized" adiabatic with irreversible mixing or splitting of the adiabatic invariant. Prototype equilibria are computed which demonstrate the working of the code. A boundary condition is varied so that the island and the plasma between the axis shrink on a mix cycle and grow on a split cycle. A specific problem of interest being studied is the nature of the transition from a three to two region problem as external constraints are adjusted until the separatrix touches the axis. At this point the separatrix becomes (adiabatically) rigid with constant internal flux.

Poster Session

Work supported by U.S. DOE Contract No. DE-AC02-76ER03077

Fokker-Planck Simulation of the Sawtooth Neutron Production on PLT*

by

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Sawtooth neutron production has been observed both on PLT[1] and on Alcator A.[2] It has an oscillation similar to the soft x-ray sawtooth oscillation emitted by electrons. To demonstrate the correlation between the two oscillations, we employ a Fokker-Planck code. Sawtooth temperature variation is imposed on the background Maxwellian electrons. Time evolution of ion temperature as well as the neutron emission are computed using PLT parameters. Comparison with experimental measurements is made.

* Work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

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Disruption Control With Helical Coils*

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The initial phase of a major tokamak disruption consists of a growing $m/n = 2/1$ magnetic island,[1] which ends in destroying confinement by interaction with other islands or with the limiter.[2,3,4] We have explored the possibility of disruption prevention through current profile control using helical coils. The helical coils are chosen with m and n values large enough so that the plasma is stable to the induced magnetic islands. The induced islands tend to flatten the current profile locally. A quasilinear single helicity analysis predicts the degree of current profile flattening produced by a helical coil at the resonant surface $q(r_s) = m/n$. Current profile flattening using coils with $m/n < 2$ stabilizes the $m/n = 2$ mode, and coils with $m/n > 2$ are destabilizing. For typical current profiles, a flattening of the profile over 15% of the minor radius at surfaces with $q = 7/4$ or $9/5$ can completely stabilize the 2/1 mode. We have verified the predictions of the quasilinear analysis with a two-dimensional initial value code which includes boundary conditions simulating external helical coils. Additional calculations are being carried out using a fully three-dimensional multi-helicity initial value code.

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* Work supported by U. S. DoE Contract #DE-AC02-76-CHO3073

† Bell Laboratories, 600 Mountain Avenue, Murray Hill, NJ 07974

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Poster Session

UCRL-85640

PUMPING OF THERMAL BARRIERS IN TANDEM MIRRORS BY INDUCED RADIAL TRANSPORT

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ABSTRACT

A localized, time varying magnetic perturbation can be used to break the third, or flux, invariant of ions trapped in a tandem mirror thermal barrier. Optimal ion removal occurs when the applied perturbation is coherent for the time of an ion drift through the localized perturbation, but incoherent on the full drift period. Properties of this pumping technique will be described including the degree of selectivity of pumping of trapped versus passing ions, the effect on hot electrons, and the required power.

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POSTER SESSION

NEOCLASSICAL TRANSPORT THEORY OF IMPURITIES IN TOKAMAKS*

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Since the comprehensive neoclassical treatment of pure electron-ion plasmas[1], there has been significant progress in developing the neoclassical transport theory for plasma containing multiple impurity ions. The efficient determination of transport coefficients for plasmas with impurity ions in varying degrees of ionization, and hence collisionality regimes, is accomplished by the use of fluid moment equations and a reduced charge state method. Both methods diminish computational requirements and enhance the physical interpretation of the Onsager matrix elements in impure plasmas. These methods are briefly discussed and used to compute the neutral beam driven current in a toroidal plasma. The application of external momentum sources to prevent impurity contamination is also analyzed, and the effectiveness of impurity reversal is compared for the direct momentum exchange and the parallel inertial forces processes. The inclusion of impurities in the ion energy balance equation is shown to produce an ohmic current driven by the relative ion-impurity flow[2,3] which can heat ions directly.

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

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Steady State Tokamaks with the Toroidal Current Driven by the Syncrotron Radiation

by

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It is proposed that a steady state tokamak is possible through the use of an anisotropic wall to preferentially reflect the syncrotron radiation in one direction and absorb the radiation that would be reflected in the other. The resulting radiation pressure sustains the current against ohmic losses. The magnitude of this effect and the current it will drive is calculated roughly including such factors as the stronger rate of emission and absorption of the radiation by the more energetic electrons and their lower rates of collisions. The effect becomes rapidly stronger with temperature and at electron temperatures of 30 to 50 Kev can drive currents of many mega amps for typical reactor parameters. Details will be presented.

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1981 SHERWOOD THOERY MEETING

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COMPARISON BETWEEN CALCULATIONS AND EXPERIMENTAL RESULTS FROM ZT-40 DISCHARGES*

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Measurements provided by the ZT-40 experimental team of low current (200 kA) discharges on ZT-40 are used in 1-D MHD transport-equilibrium calculations. The measurements include toroidal current, flux, and loop voltages as functions of time as well as preliminary measurements by point Thomson scattering of the electron temperature. The aim of the study is to employ the measurements and work "backwards" with the MHD model in order to predict/achieve agreement with the estimated values of

1. electron temperature T_e,
2. energy confinement time τ_E,
3. impurity concentration levels (oxygen and iron),
4. power losses.

The work concentrates on a particular RFP discharge with low line density and a field reversal ratio of approximately 0, e.g., spheromak configuration. Several quantities like initial spatial profiles are unknown and these are subject to variations in a series of MHD calculations.

The motivation for this work is the dramatic improvement in performance of ZT-40 with a metallic liner over that of ZT-40 with a ceramic liner. Zt-40 in its present form is one of four RFP devices with metallic liners and the data obtained from these experiments together with the modelling should provide guidance for the dependence of the energy confinement time on device parameters. Indeed when HBTX1A is in operation it should be possible to attempt to derive a scaling law since minor radii-currents vary by factors 2-3 for the RFP devices.

*Work performed under the auspices of the USDOE.

Kinetic Theory of Alfvén Wave Heating

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Heating of tokamak plasmas by Alfvén waves is studied in a linearized kinetic model which includes electron inertia and Landau damping, finite ion gyroradius, and magnetic shear. In cylindrical geometry, a fourth order set of differential equations for the perturbed fields $E_r(r)$ and $E_\perp(r)$ is solved numerically for global modes driven by a sheet current of single helicity and frequency ω, located between the plasma edge and a conducting wall. The energy deposition and density fluctuations as functions of r, and the total impedance are computed, and optimum conditions for heating are investigated. Predictions for experiments to be conducted on the PRETEXT tokamak are given, as well as nominal PLT examples. For non-axisymmetric modes, two types of results are obtained:
1) Low Q modes with the resonance layer near the magnetic axis exhibit mode conversion to the kinetic Alfvén mode and its decay by Landau damping. In these cases the plasma impedance is unfortunately small (less than one ohm). 2) High Q modes with the resonance near the edge take the form of kinetic standing waves. These may have large impedances but would result in undesirable edge heating. Axisymmetric modes and the use of density fluctuations as a current profile diagnostic are discussed in companion papers.[1,2]

This work is supported by DOE Contract DE-AC05-76ET 53036.

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FINITE β EFFECTS ON THE NONLINEAR EVOLUTION OF THE ~~(m=1;n=1) TEARING MODE IN TOKAMAKS~~*

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Numerical calculations using the reduced set of resistive MHD equations valid in the limit of large aspect ratio ($\varepsilon \equiv a/R << 1$) and high β ($\beta \sim \varepsilon$) show a β_p stabilization effect on tearing modes. In particular, the n=1 linear growth rate decreases when $\varepsilon\beta_p$ is moderately increased in a flux conserving manner. This is accompanied by a slowing down in the nonlinear evolution of this mode and a lengthening of the characteristic time for the (m=1;n=1) component to cause full magnetic field line reconnection. At higher $\varepsilon\beta_p$, the 1/1 magnetic island saturates. The stabilization is mainly due to the shift of the peak of the current density profile relative to the magnetic axis with increasing $\varepsilon\beta_p$. There is also an additional stabilizing effect due to the finite value of the pressure gradient. For even higher values of β the character of the n=1 mode changes, becoming mainly pressure driven. Although there is a stabilizing effect on the tearing modes due to increasing $\varepsilon\beta_p$, the associated distortion of the equilibrium current increases the strength of the couplings among different helicities. These couplings give rise to MHD activity extending far outside the q=1 surface, with global effects on transport. Under the assumption that the observed ISX-B MHD activity is due to tearing modes, the above results can explain some of the experimental observations.

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TRANSPORT THEORY OF A ROTATING PLASMA*

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ABSTRACT

In recent neutral beam injection experiments on tokamaks, high toroidal velocity v_ϕ of the plasma is achieved, approaching the thermal speed v_i of the main ion, and exceeding those of the heavier impurity ions. Such high velocities cannot be accomodated in the usual neoclassical theory of transport, which regards v_ϕ/v_i as first order in δ, the ratio of ion poloidal gyroradius to the plasma scale length. By expanding the drift kinetic equations in both δ and ε, the inverse aspect ratio, and including a radial electric field $-\phi'$ such that $\phi'/B_\theta \sim v_i$, we have formulated the transport problem with arbitrary rotation. In this theory, ambipolarity of the second order particle fluxes is not automatic. Its imposition determines ϕ'. Also, an angular momentum transport equation is obtained involving a cross field flux determined from the first order distribution function rather than the second as in the usual theory. While results from the usual theory are recovered in the appropriate limit so that the new theory represents a generalization, significant modifications have also been found in the regime of larger rotation. Examples are: (1) a large enhancement of impurity ion flux in the plateau regime, (2) the existence of convection as a mechanism for angular momentum transport, and (3) the transition from ν_i to $1/\nu_i$ scaling for the ion heat flux in the Pfirsch-Schlüter regime.

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2A7

Verification of the Classical Theory of Stellarator Transport*

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The apparent discrepancies of the classical theory of helical transport in stellarators, versus two recent numerical studies[1,2] of stellarator transport, are investigated. Numerical results are presented, verifying the classical theory, when the model for the magnetic field has the simple form assumed by the classical theory. When the helical contribution to the total transport is isolated numerically, and the different energy dependence of the particle distribution is accounted for, the results of one of the numerical studies[1] is brought into substantial agreement with theory. It is argued that the anomalously favorable low collisionality results of the second numerical study[2] are due partly to numerical procedure, and partly to a more complicated spatial dependence of the magnetic field. The latter may enable collisionless helical detrapping to dominate the usual collisional mechanism at low collisionality, thereby controlling transport. The implications of these findings for stellarator design are discussed.

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

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2. R. E. Potok, P. A. Politzer, L. M. Lidsky, Phys. Rev. Lett. 45, 1328 (1980).

ROLE OF BETA LIMITS ON REACTOR Q VALUE IN EBT*

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In EBT, there are two principal plasma components: toroidal core plasma where the fusion reactions occur and hot electron rings which are essential to the stability of the overall configuration. The economic viability of an EBT reactor improves significantly if $\beta_{core} > 10\%$ and average "minimum-B" stabilization requires $\beta_{ring} \gtrsim 10\text{-}15\%$. Defining a reactor Q value that is roughly the ratio of the fusion power produced ($\propto \beta^2_{core} B^4$) to the ring sustaining power [$\propto \beta_{ring} B^4 f(\gamma)$ where γ is relativistic factor and $f(\gamma)$ has a broad minimum for $\gamma \sim 2\text{-}4$], one can see the relative importance of "$\beta^2_{core}/\beta_{ring}$" on the reactor performance and economics. [Alternatively, $Q \propto n_{core} g(\gamma,B)/n_{ring}$.]

Theoretical models indicate limits on core beta ranging from a few percent (as a lower limit) to 10-30% depending on the assumptions. Basically, one of the key parameters in determining limits on β_{core} is $\varepsilon = \delta/R_c$ (stable if $\beta_{core} \lesssim \alpha\,\varepsilon$ with $\alpha \sim 2\text{-}4$) which is roughly the ring radial scale length divided by "average" radius of curvature. Because of uncertainties in extrapolating results of simplified models to a reactor geometry ε (and α) cannot be determined accurately. Also, reasonable changes within the models and/or assumptions are seen to affect the β_{core} limits by almost an order of magnitude. Hence, these limits, at the present, cannot be used as a rigid (and reliable) requirement for EBT reactor engineering considerations. However, sensitivity studies can be carried out within a reasonable parameter range to demonstrate the effects of various modes, assumptions, and models on a reactor performance. One such study has been carried out and the parametric dependence of Q on the stability boundaries has been obtained.

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Particle-Confinement Criteria for Axisymmetric Field-Reversed Magnetic Configurations*

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Particle-confinement criteria are involved in many essential calculations for fusion plasmas, e. g., evaluation of particle-confinement time, particle distribution functions, etc. Here general conditions for particle confinement are derived for an axisymmetric system and specialized to a general class of vortex-type field-reversed magnetic configurations. The criteria for closed-field and open-field confinements are obtained explicitly, including both the lower and upper bounds of P_θ/q where q is electron/ion charge. In previous studies,[1,2] only ions are considered and only the upper P_θ bound (i.e., $P_\theta < 0$) is imposed. The lower bound on P_θ/q represents a necessary condition for absolute confinement of particles. In certain limits, the commonly used criterion for Hamiltonian, $H < -\omega_o P_\theta$, where $\omega_o \equiv qB_o/mc$, is deduced from a more general form as a special case. In addition, a new criterion, $-B_o R_W^2/2c < P_\theta/q < 0$, where R_W = wall radius, and B_o = vacuum field, is found necessary to be imposed, which reduces the confined region in (E, P_θ) space. These results can be applied to calculations for Field-Reversed Mirrors and Field-Reversed Theta Pinches and examples are presented.

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Beam-Driven Currents and Heating in Tokamaks by Multi-MeV Particle Beams*

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ABSTRACT

A Monte-Carlo beam injection and tokamak orbit code is used to calculate the heating and beam-driven currents which result from injection of neutral and charged beams of selected elements from D through Si with energies of ~1 MeV/amu. The trajectories of the fast ions are obtained from integrals of the first-order guiding-center drift equations in a tokamak with concentric elliptical cross-section. Successive ionizations and finite Larmor-radius effects are included. Coulomb collisions with the (fixed) background plasma are used to calculate the plasma heating rates and perturb the ion trajectories. A fine aspect ratio trapped-electron connection is used in the calculation of the beam-driven current. Preliminary estimates of the optimum beam species, particle energy, and beam orientation are presented for an advanced tokamak, INTOR, and STARFIRE.

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poster

UCRL-85633

MONTE CARLO AND ANALYTICAL EVALUATIONS OF RESONANT TRANSPORT IN MFTF-B

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ABSTRACT

Comparisons are made between Monte Carlo and analytic evaluation of resonant transport in MFTF-B magnet designs. Either approach requires knowledge of the particle orbits in the actual field as modified by the finite beta plasma. These fields are obtained from the long-thin finite beta equilibrium code of Pearlstein et al. The Monte Carlo results are the simplest to obtain in the plateau and highly collisional regimes. In the banana regime, where collisions are weaker, the statistical requirements are more stringent. For parameters representative of operation with A-cell thermal barriers, MFTF-B lies in the banana regime. Analytic expressions for the transport coefficients are evaluated and radial transport is shown to be comparable with endloss for these parameters. Quantitative comparisons for transport are given for old and new designs where recent changes have obtained big improvements in reducing distortion due to parallel currents and in vastly improved A-cell omnigenity.

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POSTER PAPER

Development of an Ion Cyclotron Heating Package for BALDUR

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An ICRF heating package is being developed for use in the transport code BALDUR for heating studies on PLT and TFTR. It is to include a ray-tracing package for determining the wave propagation coupled to a one-velocity-dimensional Fokker-Planck module for determining the wave damping and plasma heating. The problem is characterized by three time scales: τ_w, the time for wave propagation; τ_q, the quasilinear relaxation line; and τ_t, the transport time. These satisfy $\tau_w \ll \tau_q < \tau_t$. These equations will initially be solved on a time scale between τ_w and τ_q. This allows a non-iterative steady-state solution for the wave fields while the Fokker-Planck equation is advanced in time. However, the Fokker-Planck code is written so that the time step may be taken larger than τ_q, enabling a steady state to be obtained in one step. The issues involved in a more accurate calculation of the wave fields and in a solution of the Fokker-Planck equation in two velocity dimensions will be examined.

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Prefer Poster Session

Low-m Ballooning Stability of an Axisymmetric Tandem Mirror*

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Recently the axisymmetric tandem mirror concept has been proposed[1] as an alternative to the present approach where stability is provided by highly nonaxisymmetric minimum-B end plugs. One possibility for an axisymmetric design would be to use hot electron rings to stabilize the end cells, as in the EBT experiment. Recent theoretical work has shown that this tandem mirror configuration has favorable MHD stability properties with respect to high-m (m = azimuthal mode number) ballooning modes[2] and that finite-gyroradius effects would probably eliminate the high-m modes in an experiment.[3] Thus, we consider now the stability of an axisymmetric configuration to low-m ballooning modes, which will limit the plasma β (= $2P/B^2$) in such a device.

The present stability calculation employs a simplified model of the central cell. The plasma geometry is assumed to be axisymmetric and long-thin with an isotropic, sharp-boundary pressure profile ($P(\psi)$ = const for $\psi \leq 1$, $P = 0$ for $\psi > 1$). The end cell is modeled by a stabilizing boundary condition. We have computed an upper bound on the critical beta as a function of mode number and connection length to the plug, and studied the character of the low-m eigenfunctions. Extension of this work to include a more realistic model of the end plug will also be discussed.

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*Work supported by the U. S. Department of Energy under contract DE-AC03-79-ET-53057.

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ALFVÉN RESONANCE HEATING OF A THETA-PINCH*

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ABSTRACT

An equation for the motion of linear perturbations of a θ-pinch equilibrium has been derived from a lowest-order, ion-Larmor-radius expansion of the Vlasov-fluid model.[1] This equation contains kinetic terms accounting for ion-Landau damping and ion-cyclotron resonance effects. By including ion cyclotron effects, this equation is able to describe shear Alfvén azimuthally symmetric modes which could not be expressed in previous, low-frequency, lowest-order in the ion-Larmor-radius expansions. This equation of motion is applied to the study of the heating of a θ-pinch plasma by excitation and damping of the shear Alfvén wave. The analysis shows that finite-temperature effects transform the magnetohydrodynamic Alfvén resonance into a cutoff-resonance-cutoff triplet, and that excitation of the Alfvén wave through the outermost cutoff point results in strong plasma heating by damping in the resonance region. The global heating and the spatial distributions of energy deposition, wave polarization and electric-field components are shown for a numerical calculation of a rigid-rotor equilibrium modeling the High-Beta Q Machine.[2] Results show that Alfvén resonance heating may be a rewarding heating scheme of θ-pinches. Evaluation of the local dispersion relation confirms the numerical results.

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MICROSTABILITY OF THE EBT BOUNDARY

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The relatively sharp gradients in the EBT boundary suggest that a variety of drift-type microinstabilities may be operative in that boundary and, through their contribution to anomalous transport processes, these instabilities may significantly affect the gross structure of the EBT boundary. We consider here the local stability theory of the lower-hybrid-drift ($\omega \sim \omega_{lh}$), the drift-cyclotron ($\omega \sim \omega_{ci}$), and the universal ($\omega << \omega_{ci}$) instabilities, focusing on the three-component and strong diamagnetic aspects of a plasma characteristic of the EBT boundary. Within the context of local theory, diamagnetism can stabilize these modes - a feature at variance with the often stated principle that a plasma cannot stabilize itself by digging its own diamagnetic wall. The reason for this variance is that the diamagnetism is provided by a specie (the relativistic electrons) which does not, itself, make a significant direct contribution to the dispersive properties of these drift modes. This apparent synergistic feature of EBT, whereby the diamagnetism due to the ring diminishes the microinstabilities of the core while the colder core plasma itself may have a stabilizing effect on the interchange instability of the ring, argues well for further detailed study of the EBT concept.

TRANSPORT CODE SIMULATIONS OF LOWER HYBRID HEATING IN ALCATOR C, USING A MODIFIED ELECTRON THERMAL DIFFUSION COEFFICIENT*

by

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An electron thermal diffusion of the type proposed by Coppi and Mazzacato[1] has been shown to account for experimental observations from a wide variety of ohmically-heated toroidal devices. Recently a modified form of this coefficient that is appropriate to situations in which non-ohmic auxiliary heating is important has been advanced.[2] The volume-averaged magnitude of the "non-ohmic" coefficient is typically greater than that of the "ohmic" coefficient. We have used both forms of the diffusion coefficient in transport code simulations[3] of lower hybrid heating on the Alcator C tokamak. We find that the plasma heating associated with the "non-ohmic" coefficient is considerably less than that which occurs when the "ohmic" coefficient is used.

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LOSS-CONE EFFECTS ON RELATIVISTIC ELECTRON RINGS IN EBT

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In the JAYCOR relativistic ring model, appropriate moments of the relativistic electron kinetic equation are used to determine both the evolution and steady state of ring parameters. Our earlier calculations, which included quasilinear microwave heating, synchrotron radiation and collisions, demonstrated an initial evolution in which perpendicular electron energy increased more rapidly than parallel energy. However, synchrotron radiation losses eventually clamped net perpendicular heating of electrons while net parallel heating still persisted. Eventually a steady-state was reached in which parallel electron temperature was several MeV, while perpendicular electron temperature was an order of magnitude smaller. This result is clearly consistent with the several MeV circulating electrons in the central portions of EBT, but is inconsistent with the relativistic electron ring located away from the plasma axis.

The present ring model postulates that loss-cone effects play a critical role in determining the ring momentum distribution function near the plasma edge. Indeed, our calculations including loss-cone, quasilinear heating, synchrotron radiation, and collisional effects demonstrate that the mean perpendicular electron energy is always larger than the mean parallel energy. However, the calculations also consistently show a steady-state in which synchrotron radiation still clamps the perpendicular energy because energy and electron leakage into the loss cone due to microwave interaction, synchrotron radiation, and collisions is too small. The ring temperature scaling associated with synchrotron clamping of perpendicular energy disagrees with the experimental ring temperature scaling in EBT. Consequently, classical processes must be supplemented by additional anomalous loss mechanisms such as pitch angle scattering into the loss cone by whistler instabilities in order to explain the experimental observations. Preliminary calculations including whistler interaction, indicate that this anomalous process may determine steady-state ring energy balance.

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Magnetic Noise In An Igniting Plasma

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Electromagnetic oscillations that can be described as a mixture of shear-Alfvén and interchange modes have been shown[1][2] to be able to resonate with the population of high energy particles produced by the fusion reactions occurring in a magnetically confined plasma reaching thermonuclear ignition. However, it has also been shown that for a realistic equilibrium configuration these oscillations cannot be found as normal modes. In particular wave-packets have been considered and found to undergo only a relatively small amplification due to the transient nature of their resonant interaction with the fusion products. Thus, they cannot be expected to cause a severe deterioration of the confinement time of the fusion products with the possible exception of those equilibrium configurations obtained at finite values of β that, being stable against the ideal MHD ballooning modes, can nevertheless be subject to rather large "opalescent" oscillations.

This analysis was done without explicit reference to the source term of the oscillations, i.e. either to the statistical fluctuations of the discrete particles in the plasma which, through their random motions, are ultimately responsible for the fluctuating electromagnetic fields, or to disturbances, either externally excited or produced inside the plasma by nonlinear processes, that may happen to match the properties of shear Alfvén-interchange oscillations.

Here, this analysis is extended by including the former source of noise only.[3] In this case charged fusion reaction products are found to be the most important source of noise as consistent with the fluctuation-dissipation theorem and the analysis of the resonant interaction between the oscillations and the particles in the plasma. A simple estimate of the correlation function of this source term shows however that it is unlikely that a large fluctuation level can be reached, thus confirming the results of References 1 and 2.

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NONLINEAR UNIVERSAL MODES WITH DIFFUSIVE ELECTRONS*

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ABSTRACT

In the theory of Hirshman and Molvig,[1] the stochasticity of electron orbits resulting from the perturbed electric fields of a number of modes associated with different mode-rational surfaces allows the instability to grow by providing a modification of the electron response near a given mode-rational surface. Eventually as the perturbation reaches a sufficiently high level, stochastic damping overcomes the growth rate, and the mode saturates. Calculations using a simple Krook-type operator to approximate the stochastic diffusion operator verify this prediction.[1] Here we study the same problem, but without an approximation to the diffusion operator, using an initial-value technique.[2] While we find essentially the same mode with the same qualitative dependence on the electric field amplitude, we find significant modification of the results, in that

1) the level of the diffusion level required for instabilities is higher than that of the Krook model,
2) the wave spectrum in k_x ($\equiv k_r$) is modified, and
3) the stabilizing effect of large diffusion is much less than with the Krook approximation.

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

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PERIODIC LARGE-AMPLITUDE MHD ACTIVITY IN BEAM-HEATED TOKAMAKS*

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Using the $\Delta'(W)$ finite island-width model we calculate the existence of large-amplitude, slow (diffusion) timescale MHD activity in low-β, circular beam-heated discharges. Large temperature gradients across the forming islands are found to drive an oscillation between 2/1 and 3/2 islands, which alternate in time. Faster (resistive-tearing) timescale calculations would predict disruption if the 2/1 and 3/2 were to overlap simultaneously.[1]

This "giant" periodic activity emerges from the simulation without *a priori* assumptions about its existence, and is sensitive both to the mechanism for describing transport (as affected by islands) and to the q-profile. A similar ansatz-free periodic behavior for the 1/1 sawtooth has been found by Parail and Pereversev,[2] where an alternating hollow j-reconnection cycle leads to periodic behavior. The 2/1-3/2 activity described here occurs under conditions close to disruptivity.

This low-β effect, caused by large beam-induced temperature gradients, joins a number of other beam-specific effects (Ohkawa current modification q-profile, charge exchange recombination enhancement of radiative losses, rotation-induced modification of flux-surface triangularity) which must be distinguished from authentic new high-β (or β_{pol}) phenomena. The period and amplitude are calculated to be affected by pellet deposition modifications to n_e and T_e, and by the spatial distribution of the beam induced current.

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

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POSTER REQUESTED

UCRL-85641

HYBRID SIMULATION OF OHKAWA CURRENTS

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ABSTRACT

A one-dimensional cylindrically symmetric hybrid simulation code has been developed to investigate Ohkawa currents and field reversed mirrors. A fluid description is adopted for electrons with electron inertia ignored and quasineutrality assumed. The ions are modeled as particles. Coulomb friction between the ions and electrons is introduced by means of a drag term in the momentum equations. Ampere's and Faraday's laws are solved globally and implicitly to provide self-consistent magneto-inductive effects. For cold electrons on open field lines, electrostatic effects are strongly limited and can be ignored. On closed field lines, a flux-tube averaged equation, $\oint d\ell B^{-1}\nabla \cdot (4\pi \vec{J} + \partial\vec{E}/\partial t) = 0$, determines the electrostatic potential as a function of the magnetic flux. Orbit-averaging of $\vec{J}$ in this equation greatly improves the statistical resolution.

Simulations demonstrate that an ion impurity can allow the establishment of an Ohkawa current so that a net toroidal current can be produced by tangential neutral beam injection. With no impurity the magnetic field and flux can be driven to zero by beam injection, at which point stagnation occurs and the field does not reverse. With impurity present, the field lines can close and a radial electric field can arise that significantly influences toroidal electron currents. These studies are relevant to sustaining steady currents in a tokamak or field-reversed mirror.

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POSTER SESSION

RADIAL TRANSPORT IN TANDEMS*

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At present, estimates of the radial transport in tandem mirrors are based on the behavior of the ions.[1-3] However, we demonstrate that the appropriate flux surface average of the "radial" current density must vanish. As a result, radial transport and end loss <u>must</u> be viewed as <u>independent</u> ambipolar processes. Consequently, the electrons may be employed to obtain an expression for the particle loss rate which (unlike the ion expression) is insensitive to the self-consistent ambipolar electric field (and may be compared with the ion end loss expression). Demanding that the ion and electron radial losses be equal then determines the local value of one component of the electric field (usually the radial component). Because the ion radial losses are associated with a small fraction of the ions, the particle loss rate may often be multiplied by a typical energy to obtain a meaningful estimate of the radial ion energy flux.

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POSTER SESSION

TEARING MODE STABILITY OF A GENERAL CROSS SECTION TOKAMAK*

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ABSTRACT

Tearing mode stability in a general cross section tokamak is studied by employing a neighboring equilibrium formulation. Multiple singular surfaces may be present even for monotonic q profiles. The stability boundary in terms of the equilibrium parameters is presented. The magnetic field configuration at mode saturation is determined by considering the energy flow in the inductive island growth regime.

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Whistler Instability of the Thermal Barriers†

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The thermal barriers[1] are considered important for the effective operation of the tandem mirror machines. The anisotropic electron distribution that is present in the barriers is unstable with respect to electromagnetic modes. Assuming a bi-Maxwellian electron distribution, the linear analysis of these modes is carried out in the regime of parameters relevant to MFTF-B. In spite of the convective character of these instabilities, the growth rates are found to be sufficiently large that they lead to the isotropization of the electron distribution and, therefore, to the deterioration of the barriers. Quasilinear theory[2] is used to find the power necessary to sustain the barriers in the face of this instability.

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

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2B18

Effects of Poloidal Electric Field on EBT Transport

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ABSTRACT

We present here the results of numerical computation for EBT transport that includes the effects of the poloidal electric field ϕ_1. We consider the collisional case where the ion collision frequency ν_i is comparable to the typical precession frequency Ω_o and use the Krook collision model. The components ϕ_c and ϕ_s of $\phi_1 = \phi_c\cos\theta+\theta_s\sin\theta$, θ being the poloidal angle, are found to be of the same order of magnitude. These components are numerically solved from two coupled Fredholm integral equations, and the result is used in the evaluation of particle and energy fluxes. Our numerical results show that:

i) For $T_e/T_i \sim 1$, the energy flux and the radial electric field are changed up to 100% by including the contribution due to ϕ_s and ϕ_c.

ii) For $T_e/T_i \sim 5$, the inclusion of ϕ_c and ϕ_s changes the energy flux by two orders of magnitude.

We also examined the collisionless limit $\nu_i/\Omega_o << 1$ and found drastic change of the energy flux by the inclusion of ϕ_1. This result suggests that the effects of ϕ_1 may also be significant in the collisionless transport when Fokker-Planck collision terms are used.

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Derivation of Equations Describing Mode-Conversion and Tunneling Using a Variational Principle*

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A variational method for deriving equations to describe the effects of localized absorption and mode conversion for rf waves in a fusion type plasma will be presented. This is an adaptation of the method developed by H. L. Berk and R. R. Dominguez.[1] Traditionally, a uniform warm plasma dispersion relation, pertaining to the particular process studied, is obtained; then inhomogeneities are introduced by replacing the k vector in the direction of the inhomogeneity by a derivative operator. This technique leaves some ambiguity in the equation as to which terms are to be differentiated. The variational method develops the wave equation in k-space as does the uniform plasma theory. However, instead of selecting a particular k-mode, an integration is performed over all k-modes in the direction of the inhomogeneity. The application of the exact variational integral would lead to a coupled set of integral equations. A useful approximation scheme exists in which the variational integral is expanded in k-space, and then converted to x-space with a definite prescription of the ordering of the operators. This approximate integral leads to a set of coupled differential equations.

The general variational integral is developed here for the plasma slab model where the magnetic field is chosen in the z-direction with gradients in the x-direction. For the cases considered the drift velocities due to the inhomogeneities are neglected. The terms necessary to describe heating at the first two harmonics of the ion cyclotron frequency are calculated to second order in the ion Larmor orbit. The specific case of second harmonic heating is treated in detail.

* Supported by McDonnell Douglas Corporation Independent Research and Development Program

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THE EFFECT OF CUSP AND MIRROR COILS ON FIELD LINE RECONNECTION IN A FIELD REVERSED THETA PINCH*

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A field reversed configuration is formed in a reverse field theta pinch when oppositely directed magnetic field lines connect at the ends of the device. The effects of cusp and mirror fields on reconnection have been studied with a two-dimensional magnetohydrodynamic computer code. The reconnection process is found to be dependent on the dynamic motion of the plasma away from the magnetic x-point. This motion arises from endloss (moving outward) combined with axial contraction (moving inward) of plasma carried on closed field lines. Increasing the quantity of trapped bias flux is found to increase the rate of plasma flow away from the x-point and consequently the reconnection rate.

Numerical simulations in the parameter range of the FRX-B[1] experiment at LANL show that mirrors can play a significant role in magnetic field line reconnection. In simulations where the theta pinch coil is assumed to be shaped to produce a 10 percent mirror field on axis, the magnetic field lines rapidly reconnect and form a field reversed configuration. However, when a straight theta pinch coil is assumed, the field lines do not all reconnect. Good qualitative agreement has been found between the calculations and the experiment.

Numerical simulations have also been made in the parameter range of the CT-TRX1[2] experiment at MSNW. These calculations show that the timing of field line reconnection can be controlled by using a cusp coil to delay reconnection and then firing a mirror coil to trigger reconnection when desired.

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NEOCLASSICAL RESISTIVE $q(\psi)$-CONSERVING-TOKAMAK EQUILIBRIA*

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In previous studies of the plasma properties required to give resistive equilibrium and preserve ideal M.H.D. stability, it was found that for the highest $\bar{\beta}$ stable equilibria, a hollow temperature profile resulted.[1] Since α particles should preferentially leave their energy at the pressure peak in a reactor like plasma, these hollow temperature profiles would appear to be inconsistent with such a plasma. Spitzer resistivity (with and without neoclassical corrections[2]) was used. For a well-behaved reactor (i.e., one not beset with turbulence or other anomalous transport phenomena), a full neoclassical treatment would be appropriate because of the low collisionality. Starting with neoclassical theory, a differential equation for the density (with electron temperature as input) can be found which gives the density profile required for resistive equilibrium satisfying $\partial q/\partial t = 0$. This differential equation has been used to seek regions of parameter space where resistive equilibrium, ideal M.H.D. stability and reactor like temperature profiles can simultaneously be found. The only parameter region found so far has $T_i > T_e$ and corresponds in some sense to the "hot ion mode,"[3] which is unfortunately strongly affected by losses from field ripple.[4] So far then, the search for resistive equilibria stable to ideal modes at moderately high beta has not led to completely acceptable configurations.

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*Research sponsored by the Office of Fusion Energy, U. S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.
†Located at the Office of Fusion Energy, Department of Energy, Washington, DC.
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Magnetic Field Reconnection Rates*

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A 2-D resistive MHD code[1] is used to investigate the magnetic field reconnection rates in two contrasting cases; i.e., the magnetic island formation induced by an external helical coil and the spontaneous island growth due to $m > 1$ tearing instability. In the induced reconnection process, we find a Sweet-Parker type[2] reconnection layer structure. However, Sweet-Parker scaling is not valid when the viscosity μ is much larger than resistivity η (in scaled units). In such a case, the reconnection rates can be derived as $\dot{\psi}_s \sim \eta^{3/4} \mu^{-1/4}$. This scaling agrees well with the numerical results. In the case of $m > 1$ nonlinear tearing modes, we find the reconnection rates scale as $\dot{\psi}_s \sim \eta$ which agrees with Ref. 3. One implication of these results is that in disruption control schemes using external coils,[4] the induced island can be formed much faster than the $m > 1$ unstable island growth for small η.

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

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POSTER SESSION

STATISTICAL MAGNETOHYDRODYNAMICS OF A REVERSED-FIELD PINCH*

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The state of an incompressible 3-D ideal magnetofluid bounded by a cylindrically-symmetric perfect conductor can be represented by an infinite set of spectral coefficients.[1] In the phase space spanned by the real and imaginary parts of these coefficients, we have verified that the dynamical evolution of the magnetofluid satisfies the Liouville theorem. In the absence of any cross helicity, we thus assume that the distribution of the spectral coefficients representing the magnetic field is described by the absolute equilibrium ensemble, $\exp[-2\mu_o(W_B-\mu K)/\varepsilon]$, where W_B and K are the magnetic energy and magnetic helicity, respectively. Our new representation avoids the Gibbs phenomenon implicit in earlier work,[2] although K now has a double-sum structure.

Our model[3] predicts magnetohydrodynamic fluctuations about a cylindrically-symmetric, Bessel-function-model mean magnetic field. The spectral density tensor of these fluctuations has been calculated. A simple pole, associated with the parameters of Taylor's helical state,[4] occurs in this tensor. As a result, the range of Taylor's Θ parameter for the mean magnetic field is restricted to values less than 1.6. As the Θ of the mean field approaches 1.6, the band of ℓ and m values contributing significantly to the tensor narrows down to those values associated with Taylor's helical state. This narrowing may bear upon the nature of the "quiescent" period of reversed-field pinch operation.

We shall also discuss the necessity of viscosity and resistivity for vitiating the assumption of energy equipartition at high wave number. These non-ideal effects lead phenomenologically to a version of this statistical model having a truncated spectrum. In this version, the effects of both the mean and fluctuating magnetic fields upon the mean pressure confined would be calculable.

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MINIMUM ENERGY TOROIDAL EQUILIBRIA

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In a recent paper[1], we have constructed equilibria with minimum energy from a variational principle with global invariants. We now present toroidal solutions of the equilibrium equation. In computing equilibria numerically, we exploit our variational principle to obtain a reduced set of ordinary differential equations for the inverse problem in axisymmetric toroids[2]. The procedure is analogus to that used in Ref. 3 which, however, employs a different variational principle. We explore the "tokamaklike" and "pinchlike" windows[1] of minimum energy states in toroidal geometry. Implications for ideal and resistive stability of these equilibria are discussed.

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MHD Stability Near The Magnetic Axis of a Compact Toroid*

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We consider in this paper an axisymmetric toroidal plasma in which the toroidal field can range from zero, as in the case of a field-reversed mirror, to a value comparable to the poloidal field as in the case of spheromak. We obtain solution to the Grad-Shafranov equation near the vortex by keeping only second order terms in the cylindrical coordinates (r , z) which characterize the flux function. Because of azimuthal symmetry the perturbation to which the equilibrium is subjected can be expressed in terms of its Fourier components. Using the energy principle we examine the stability of localized, incompressible, interchange-type modes with toroidal and poloidal mode numbers given by "m" and "n" respectively. With " q " being the familiar safety factor we find that for $n \geq 1$ and all m the system is stable if $q \neq 0$. Moreover, we find that the (n = o,m) mode is stable if $q^2 > \frac{1}{m^2}$. We conclude that a sufficient condition for the stability of these modes near the magnetic axis is $q^2 > 1$ which is in agreement with the Mercier criterion. This study further shows that systems with only poloidal fields can be stabilized by the addition of a "weak" toroidal field.

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The Effects of Parallel Currents on Tearing Modes

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ABSTRACT

One important omission in the current theories of collisionless tearing modes is the presence of toroidal currents in Tokamak plasmas. It has also been noted[1] that in the central region of the plasma the drift velocity can exceed the ion sound speed so the modifications due to currents could be sizeable. A simple slab model theory for tearing modes in the presence of toroidal currents is presented. We use the variational methods of Mahajan et al[2] and the code EMDRIFT[2] to approach the problem both analytically and numerically.

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POSTER SESSION

A VARIATIONAL METHOD FOR THE EVOLUTION OF TOROIDAL PLASMAS

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The time-dependent self-reversal of a slightly dissipative plasma in arbitrary toroidal configuration is investigated by minimizing its total potential energy subject to total mass conservation and constancy of the magnetic helicity[1] $K = \int_V \underline{A}\cdot\underline{B}\, dV$. The gauge for $\underline{A}$ is chosen to insure its single-valuedness. The equations of steepest descent are obtained for the flux function, as well as the toroidal and poloidal flux profiles. An existing equilibrium and stability code[2] has been modified to include these features. As the potential energy decreases along the path of steepest descent, the plasma undergoes the intermediate states through field reversal.

Defining an equilibrium state by the difference between the magnetic and pressure forces to be below 1%, we anticipate non force-free configurations. The relaxation to the force-free configuration will occur on a much longer time-scale.

Work supported by US Dept. of Energy-

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Hamiltonian Field Formulation of Two-Dimensional Vortex Fluids, Guiding Center Plasmas and the One-Dimensional Vlasov-Poisson Equations

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Recently we obtained Poisson brackets which cast ideal MHD[1] and the Maxwell-Vlasov equations[2] into Hamiltonian form. Here we discuss the Hamiltonian field description of the equations which describe two-dimensional vortex fluids or equivalently guiding center plasmas.[3] A Poisson bracket is given in terms of the vorticity (charge density), the physical although noncanonical dynamical variable. The well-known constants of motion are seen to be in involution with respect to this bracket. This noncanonical formulation is transformed into a canonical one. A spectral representation is obtained which has a quartic interaction Hamiltonian. The one-dimensional Vlasov-Poisson equations are seen to possess the same Poisson bracket as that for the fluid. Here one observes in the spectral representation that the Hamiltonian contains quadratic as well as quartic interaction terms.

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

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1981 SHERWOOD THEORY MEETING
Austin, Texas - April 8-10, 1981

MAGNETIC RECONNECTION AND ISLAND FORMATION IN NONEQUILIBRIUM FIELD REVERSED CONFIGURATIONS: THE EFFECT OF FINITE THERMAL CONDUCTIVITY*

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Magnetic field topology changes play an essential role in the explanation of observed behavior in many systems with strong magnetic fields. Understanding of the reconnection phenomena is essential for explaining the formation of the various compact tori or spheromak containment schemes. Nonequilibrium reconnection has been simulated with a hybrid (kinetic ions; zero-mass, thermal fluid electrons) model which is quasi-neutral, axisymmetric, and radiation free.[1]

An implosion has been simulated by applying a positive external B_z to an initially homogeneous plasma that is saturated with a negative bias field. By following the implosion through time, reconnection at the resulting field null is found to occur at least an order of magnitude faster than predicted by linear growth rates from resistive MHD theory.

Since nonequilibrium processes are by definition highly dynamical, a detailed analytical description of the process is quite difficult. However, there are several aspects of the process that can be explained qualitatively with quantitative estimates of the time scales involved. Among the observations are: a) The early nonequilibrium dynamics wherein the ions are driven inward at twice the magnetic piston velocity. b) The ions are reflected from the reversed bias field, during which time axial perturbations of the reversed bias field lines occur. During this stage, a significant amount of localized toroidal magnetic field (B_θ) is produced, however, there is no net toroidal flux. c) Nonlinear bouncing of the ions between the two regions of antiparallel fields follows, with the bias field line perturbations focusing the secondary reflected ions into the positive bias region, thereby causing clumping of ions localized near the field null. Concurrently, during this stage, small scale island structures develop. d) Nonlinear coalescence of the small scale islands into larger islands rapidly follows. Also, during this stage, the B_θ field is annihilated. e) After coalescence a quasistationary equilibrium stage occurs wherein no significant dynamical processes take place.

Initial results were obtained with a simplified T_e representation with constant resistivity. Recently, a self-consistent T_e equation has been added to the procedure along with Spitzer resistivity and thermal conductivities. Early indications are that the reconnection occurs on the same rapid time scale and the ensuing island formation procedes even more rapidly.

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*Work performed under the auspices of the USDOE.

POSTER SESSION REQUESTED

LOWER-HYBRID-DRIFT INSTABILITY IN THE EBT BOUNDARY LAYER

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Although the bulk plasma gradients in EBT, as experimentally inferred, are quite weak ($\rho_i/L_N << 1$), the gradients at the plasma edge or boundary layer can be substantial ($\rho_i/L_N \gtrsim .1$). In such boundary layers, experience has indicated that anomalous transport processes associated with high frequency drift wave microturbulence are comparable to or even dominant over classical transport processes. However, in contrast to other devices with sharp edges, EBT possesses unique features, e.g., relativistic electrons and a diamagnetic well, which could strongly affect drift wave stability properties. We present here a nonlocal linear stability theory of the lower-hybrid-drift instability, a particularly virulent high frequency drift mode, in a model EBT geometry. Basically, we find that while such effects as the diamagnetic well act to diminish the LHD, the mode remains unstable in EBT with eigenmodes that span a significant portion of the boundary layer.

1981 SHERWOOD MEETING
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THE UNIVERSITY OF TEXAS
AUSTIN, TEXAS

Nonlinear Steady-State Coupling of LH Waves by a Waveguide Array

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ABSTRACT

The coupling of lower hybrid waves at the plasma edge by a two waveguide array is solved in the steady state taking into account self-consistent density modulation due to ponderomotive effects. The unperturbed plasma assumes a linear density profile and only the fundamental mode in the waveguide is considered. Numerical solutions show that at high power levels the plasma admittance is reduced in the presence of ponderomotive density depressions which leads to a change in the reflectivity. The dependence of reflectivity on incident power and the phasing between waveguides is evaluated. Although the excited wave is spectrally broadened, the bulk of the power spectrum exhibits a downshift towards lower parallel wavenumbers. The nonlinear modification of the linear cutoff surface caused by density rippling results in a significant enhancement of the spatial fields up to where the resonance cones separate.

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Electron Cyclotron Resonance Heating of MFTF-B at Relativistic Energies*

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A ray tracing code has been developed to study ECR heating of tandem mirrors. The code is in cylindrical geometry and can use either Hermitian or non-Hermitian dielectric tensors for the rays. We will show numerically that the ray trajectories of 'warm' and 'cold' plasmas are almost identical for energies up to 200 KeV. In most cases, ray tracing with non-Hermitian dielectric tensor will be sufficient. An analytical justification is also given by H. Weitzner and D. Batchelor.[1]

The absorption is $A = \exp\left(\int -2\Gamma dt\right)$ where $\Gamma = -D_i/(\partial D_r/\partial\omega)$, and D_r and D_i are the real and imaginary parts of the determinant of the dielectric tensor. D_i and D_r are calculated fully relativistically, arbitrary large values of relativistic γ can be used, i.e., we do not use Shkarofsky's integrals[2] which assumed $\gamma \sim 1$. Absorption of the first and second harmonics of the ordinary and extraordinary modes at hundreds of KeV can be calculated. Results of ECR heating of MFTF-B will be presented.

*Work supported by U. S. Dept. of Energy Contract No. DE-AI01-76ET53020

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POSTER SESSION

RELAXATION OF MAGNETIZED PLASMAS*

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ABSTRACT

In a recent Physical Review Letters,[1] the author reported that the effective shielding length evaluated from high frequency conductivity is the Debye length even for strongly magnetized plasmas. As an alternative approach, this can be proven by a kinetic equation for a magnetized plasma including collective motions.

In this paper, we show the derivation of the kinetic equation based on the B-B-G-K-Y hierarchy. The resultant equation, analogous to the Balescu-Lenard equation, is convenient for analyzing the effects of the magnetic field on particle collisions. Contrary to earlier predictions, but in agreement with the previous numerical evaluation,[1] the shielding length is found to be the Debye length in general either for e-i collisions or for e-e collisions. The equation has been applied to estimate the relaxation of the superthermal electron tail.

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*Work supported by the Department of Energy, Contract DE-AT03-76ET51011.

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NONLINEAR COUPLING OF LOWER HYBRID WAVES.

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ABSTRACT

The nonlinear coupling and propagation of lower hybrid waves excited by a waveguide array are examined numerically and analytically in a model of an inhomogeneous edge plasma in a Tokamak. The nonlinearity is the ponderomotive force which results in self-modulation of the lower hybrid waves, through the density term $n = n_0(x)\exp\left(-|E_z|^2/E_T^2\right)$ where $E_T^2 = 4m_e\omega^2(T_e + T_i)/e^2$ and E_z is the parallel component of the electric field. The geometry is two dimensional and we examine propagation in the vicinity of the waveguide apertures. We evolve self-consistently the fields in time to a steady state, by solving numerically the partial differential equation of wave propagation. We consider both travelling wave ($\phi = \frac{\pi}{2}$ progressive phasing) and standing wave ($\phi = 0, \pi$ phasing) excitations. For each case, the dependence of the plasma admittance on nonlinearity is studied, and found to scale as predicted by simpler ordinary differential equations[1]. In the travelling wave case, this confirms the validity of the one dimensional analysis by Chan and Chiu[2], and Fukuyama[3]. In accordance with these semi-analytic models, power reflectivity in the waveguides can change appreciably. We also consider nonlinear modifications of the parallel power spectrum, after propagation through the coupling region. For the travelling wave, we observe moderate broadening and downshifting of the spectrum. The spectrum remains unidirectional, that is little power is coupled to waves with negative k_z. This is of importance in current drive at large powers. In real space, the resonance cone of the travelling wave penetrates into the plasma at a steeper angle to the magnetic field, and develops a shock structure. For the standing wave, beating of positive and negative k_z's leads to generation of spatial harmonics. This broadens and upshifts the spectrum [4,5], and in real space results in filamentation of the fields. In particular, a considerable amount of power below accessibility may be transferred to an accessible part of the spectrum by nonlinear coupling. This suggests that a linearly "poor" coupler for plasma heating (e.g. a single waveguide) may be improved by nonlinear effects. Finally, we observe at very large nonlinearity that the fields may "punch through" the nonlinear region, and access directly the high densities which lie beyond the limiter shadow. In this extreme case the power spectrum is not greatly modified, but the plasma admittance seen by the waveguide is changed appreciably.

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TRANSPORT STUDY OF ISX-B FLUX-CONSERVING TOKAMAK HEATING SCENARIOS*

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Theoretically, one way to achieve high $\bar{\beta}$ in advanced devices is through a flux conserving tokamak (FCT) sequence of equilibria. The recent achievement of high $\bar{\beta}$ in the ISX-B device[2] by strong beam heating (such that $\tau_E << \tau_s$, the classical skin time, was satisfied) suggests a detailed numerical study and comparison with the earlier analytic FCT theory in order to better understand the heating process and possible $\bar{\beta}$ limits. For the resistive diffusion of $q(\psi)$ the 1-D theory of Nelson and Grad[3,4] is used. Energy and particle transport are described by simple equations containing radially varying heat and particle sources and appropriate bulk confinement times. These transport equations are coupled with a free boundary equilibrium code capable of time dependent shaping of the flux surfaces, and plasma current, with the plasma position kept constant. Preliminary results confirm the existence of approximately flux conserving regimes for ISX-B like parameters, as long as only classical field diffusion processes are admitted.

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

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TOKAMAK CURRENTS DRIVEN BY A PULSED RELATIVISTIC ELECTRON BEAM*

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The availability of high current relativistic electron beam (REB) generators and the interest in non-inductively driven toroidal currents in tokamaks motivates a study of the REB for current drive applications. We consider repetitively pulsed REB injection into a tokamak to maintain a low-ripple toroidal current. The total current, I, derives from two contributions, the suprathermal ("beam") electron velocity moment and the bulk plasma electron drift velocity. We follow the evolution of the bulk plasma current density with a momentum balance in which the bulk electron momentum changes due to collisional momentum transfer from the beam electrons, ion drag, and the self-induced emf, given by -LdI/dt. The beam current density is determined by the relativistic Fokker-Planck equation [1]. For cases of interest (injection energies $\gtrsim 1$ MeV and electron densities $n \approx 10^{20}$ m^{-3}) the emf has a negligible effect on the beam dynamics, and the resulting circuit equations may be solved analytically.

Averaged over time, the ratio of current density, j, to heating power density, p, is found to be a function of only n and γ_0, the ratio of injected electron energy to rest mass energy. Defining the normalized quantities, $\hat{j} = j/(nce)$ and $\hat{p} = p/(nmc^2\nu)$, where m is the electron rest mass and c is the speed of light, and with the characteristic energy loss frequency $\nu = \omega_p^4 \ln \Lambda/(2\pi nc^3)$, we find $\hat{j}/\hat{p}$ increases monotonically with γ_0, and $\lim_{\gamma_0 \to \infty} \hat{j}/\hat{p} = 2$. A reactor (STARFIRE) with $n = 1.2 \times 10^{20}$ m^{-3}, I = 10.1 MA and R = 7.0 m, would require at least 64 MW of REB power deposited in the plasma.

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Ion Thermal Conductivity for a Pure Tokamak Plasma

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Previous authors have calculated the ion thermal conductivity, but the results are limited by the assumption of large aspect ratio and by the usage of simplified collision operators. In particular, the Pfirsch-Schluter contribution which has previously been neglected or incorrectly treated for low collision frequencies can be important for small aspect ratios.

In this work, the ion thermal conductivity is calculated for a wide range of aspect ratios and collision frequencies. The calculation is done by solving the drift kinetic equation, with a model collision operator, with a finite element method, and then using the energy weighted friction force to determine the heat flux. The thermal conductivity, determined from the heat flux, is then curve fitted to analytic formulas. These formulas allow the conductivity to be calculated at all collision frequencies and aspect ratios down to about 3. The two main results of these calculations are, first, energy scattering increases the thermal conductivity, over values previously calculated, by a factor on the order of 1.5-2 and second, the Pfirsch-Schluter contribution becomes significant at low collision frequencies, when the aspect ratio is small. Comparisions of the thermal conductivity with the results of previous authors are given. Also presented, is the distribution function for various collision frequencies, aspect ratios and collision operators.

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POSTER SESSION

ANOMALOUS IMPURITY ION TRANSPORT DUE TO MAGNETIC FLUCTUATIONS*

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ABSTRACT

Stochastic behavior of magnetic field lines has been invoked to explain anomalous electron transport in tokamaks. The relatively slow ion transport in the stochastic field can still be comparable to the neoclassical rate. However, the rapid loss of electrons compared to ions may give rise to a positive ambipolar electric field[1]

$$E_r = - \frac{T}{e} \frac{\partial}{\partial r} \ln(nT^{1/2}) \quad ,$$

which expels ions and results in an outward convection velocity. The anomalous outward flux of impurity ions

$$\Gamma_{AI} = - D_{st} \left(\frac{2T}{2m_I}\right)^{1/2} \left[\frac{\partial n_I}{\partial r} + n_I \left(\frac{(1 + Z_I)}{T} \frac{\partial T}{\partial r} \frac{Z_I}{n_i} \frac{\partial n_i}{\partial r}\right)\right] \quad ,$$

due to magnetic fluctuations can exceed the neoclassical inward flux. Using a trace impurity code TRAIT, we have demonstrated the effectiveness of the outward convection in controlling the temporal behavior of the impurity line brightness. The stochastic magnetic fields could therefore be responsible for the observed decays of line emission from high charge states of silicon in an impurity experiment in Alcator.[2]

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FIELD LINE RECONNECTION ON A HYDROMAGNETIC TIME SCALE

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When the islands are being formed in a reversed field configuration, fast magnetic field line reconnections occurring on a MHD time scale (seemingly independent of resistivity) are observed. Later on, once the tilting of the islands take place, field lines also reconnect rapidly, thereby spilling out the contained plasma.[1]

We investigate this rapid field line reconnection using the MHD particle code in 2 1/2 dimensions. With smoothly changing magnetic field from positive to negative y, $B_x \propto y/a$, and with high density plasma at the singular layer of size a (to preserve perpendicular pressure equilibrium when no toroidal field is applied), we observe little or very slow magnetic field line reconnection for a plasma of very low resistivity. In order to initiate a fast reconnection, we perturb the high density plasma near the singular surface: $v_x(x) = v_0 \tanh((x-L/2)/\delta)$, with $\delta << L$, L being the length of the system. When v_0 is lower than the sound speed, the field line does not reconnect: when supersonic ($v_0 > c_s$), rapid hydromagnetic time scale reconnection is observed; the velocity threshold is however much lower when a gravitational force is present. When we try to initiate a reconnection by pinching a portion of the singular layer, again there is a threshold strength for pinching. In all cases observed, the density goes to zero at the x-point when fast reconnection occurs. This seems to be a necessary condition because the field line element $d\underset{\sim}{\ell}$ and $\underset{\sim}{B}/\rho$ obey the same equation $d(\underset{\sim}{B}/\rho)/dt = (\underset{\sim}{B}/\rho)\cdot\underset{\sim}{\nabla}\underset{\sim}{v}$ and the reconnection demands $d\underset{\sim}{\ell}$ be singular at the x-point. So that $\underset{\sim}{B}/\rho$ is also singular even though $\underset{\sim}{B}$ may vanish.

This work supported by the Department of Energy, Gra... Numbers DE AM03-76SS-00010 and DE FG05-80ET-53088.

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FLUID INSTABILITY OF FIELD-REVERSED THETA PINCHES

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Field-reversed theta pinches have been observed to exist for many Alfven transit times in spite of the fact that many fluid calculations for particular equilibria have found instability. This state of affairs has led to the pursuit of two possible resolutions of this conflict. The first is the search for large gyroradius effects which may cause stabilization of the system. The second is the search for particular equilibria which might be fluid stable.

In particular, we mention Newcomb's examination[1] of the linear magnetohydrodynamic equations for a field-reversed theta pinch near the null. He showed that if the flux function has nonvanishing second derivatives at the null, then the system is unstable, with a growth time equal to the magnetohydrodynamic transit time around the field line divided by 2π. However, one could argue that Newcomb's result does not resolve the question of fluid stability, since it does not apply, for example to systems with vanishing current at the null.

In the present work we examine the fluid stability question by analyzing the energy principle for the linearized double adiabatic equations in the limit of large toroidal mode number. We find that the stability of the system depends on the properties of the integral of $\kappa r B^2$, where κ is the curvature, around a closed field line. If over some region this integral increases with distance from the magnetic null, the field lines in that region are unstable. This implies that a system with one closed field line on which the curvature does not change sign must be unstable. Naturally, since the present result is based on the double adiabatic equations, the comparison theorems imply it also for the adiabatic (or Kruskal-Oberman) and magnetohydrodynamic equations.

This result can be applied to linear geometries such as EXTRAP, which is a z-pinch of noncircular cross section. We find that a field line is unstable if it exists entirely within a region where the determinant of the second derivative matrix of the flux function, $\det(\underset{\sim}{\nabla\nabla} A)$, is negative. ($\mathrm{Det}(\underset{\sim}{\nabla\nabla} A)$ is also known as the Gaussian curvature of the flux surface.) This criterion is particularly easy to apply, as we show by considering a simple model of EXTRAP.

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

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TEARING MODES IN STELLARATOR-TOKAMAKS*

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The nonlinear evolution of tearing modes is studied for a hybrid Stellarator-Tokamak. The effects of a static nonresonant helical field produced by an external coil are investigated in cylindrical geometry. The coil has poloidal mode number ℓ_{coil} and longitudinal mode number N_{coil}. The evolution of the width of an unstable island can be a strong function of N_{coil}, giving a result which differs considerably from the average method,[1] which is valid for $N_{coil} \gg n_{mode}$. In the $\ell_{coil} = 2$ cases studied, there exists a critical value of the external rotational transform, ι_{ext}, above which the unstable tearing mode under study becomes stable. However, the critical value of ι_{ext} can change by as much as a factor of two as N_{coil} is varied.

The m/n = 1 mode is studied for the ($\ell_{coil} = 3$) case of a parabolic rotational transform, $\iota_{ext}(r) = \iota_0 + \iota' r^2$. Both resistive and ideal modes can be unstable.[2] This can be compared with the limiting cases ι_{ext} = const (for which the ideal mode is marginal) and $\eta \to 0$ (where the resistive mode is absent).

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Zero-Dimensional Confinement Modelling of a Field-Reversed Configuration*

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The lifetime scaling of Field-Reversed Configuration (FRC) plasmas is an issue with crucial bearing on the size and attractiveness of potential fusion reactors. Although past experiments have yielded quite limited information about the decay of such plasmas, results from new experiments should give a much clearer picture of these processes. A valuable theoretical tool for modelling these results is a zero-dimensional global plasma model. Attractive because of their simplicity, such models yield significant inferences about the nature of the plasma and energy transport.

An example of such a global plasma model was that developed by Klevans,[1] and used to model the FRX-B experiments at Los Alamos. This model employs a truncated rigid rotor description of the plasma in which the various plasma parameters (peak density, temperature, radius, length) and the shape factor appearing in the rigid rotor profile are time-dependent. The conservation equations in the form of a coupled set of ordinary differential equations govern these variables.

A weakness, however, of the truncated rigid rotor description is that it does not permit a self-consistent description of the plasma on open field lines. The open line plasma rapidly streams away out the ends and thus is characterized by relatively low density, whereas the rigid rotor profile generally forces a relatively large density at the separatrix.

A way to circumvent this difficulty is to employ a more sophisticated model profile than the truncated rigid rotor. In particular a profile family containing <u>two</u> shape parameters would allow an equation to be added which models the interaction of open and closed line plasmas. This equation would cause the cross-field diffusion at the separatrix to balance the end streaming from the thin sheath of plasma outside the separatrix.

A model profile with these properties is described. Preliminary results are presented on how the choice of a transport mechanism affects the evolution of the plasma equilbrium.

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Gyrokinetic Approach in Particle Simulation*

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Gyrokinetic treatment of the Vlasov equation has long been used by the theorists for studying low frequency microinstabilities in a magnetically confined plasma. It is based upon the assumptions that 1) the gyroradius is much smaller than the density scale length ($\rho/L_n \ll 1$), 2) the characteristic frequency is much lower than the cyclotron frequency ($\omega/\Omega \ll 1$), and 3) the parallel wavenumber is much smaller than the perpendicular wavenumber ($k_\parallel/k_\perp \ll 1$). We have now developed a particle simulation model in the slab geometry using the same approach. Following the technique first suggested by Catto [Plasma Physics 20, 719 (1978)] in which the particle variables ($\underset{\sim}{x},\underset{\sim}{v}$) are first transformed to the guiding center variables ($R,v_\perp,v_\parallel,\phi$) before taking the gyro-phase-averaging, we have been able to obtain a nonlinear equation which contains the gyroradius effects and is also suitable for particle pushing. In the model, electrons and ion are treated as guiding center particles and are acted upon by different gyro-phase-averaged potentials. Poisson's equation has also been modified to include the ion polarization effects and the response to the ion density variations. With the present model, we are now able to push articles in ω^* time scale. Furthermore, the simulation plasma is rather quiet since the fluctuations associated with high frequency oscillations are completely eliminated. Results from the present model agree well with those from the conventional particle simulation code. Details will be presented along with their comparisons with the theory.

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Shear Alfvén Transport of Fast Alpha Particles*

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Shear Alfvén transport of fast fusion products has received attention both as an energy loss mechanism and for alpha particle ash removal.[1-4] We have developed a conceptual model of 1-D radial, fusion product transport due to a shear Alfvén mode to study the energy loss from the plasma as a function of radius, r. Widely spaced Alfvén surfaces should result in a driven $\vec{E}_\theta \times \vec{B}_0$ transport mechanism for $\omega = k_\parallel v_A << \Omega_i$. However, for overlapping eigen modes[4] the transport mechanism may be diffusion-like with a flux $\vec{\Gamma} = n_\alpha \langle\vec{v}\rangle = -D_\perp \nabla n_\alpha$.

In our model, the perpendicular diffusion coefficient $D_\perp \simeq \frac{(\Delta r)^2}{\Delta\tau} \simeq |\langle\vec{v}\rangle|^2 \Delta\tau$, where the effective velocity $\langle\vec{v}\rangle$ results from the local effective $\vec{E}_\theta$ fluctuation field. Taking $\langle\vec{v}\rangle \simeq -D_\perp \nabla \ell n(n_\alpha)$ we derive a first order partial differential equation for the resonant alpha particle number density. The equivalent system or ordinary differential equations is then solved beginning with an initial radial alpha particle distribution. At each integration time step and radial point the local electrical field is increased or damped in a self-consistent fashion according to the local resonant alpha number density, the local average resonant alpha energy, and the linear growth or damping rates.

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CALCULATION OF NON-AXISYMMETRIC MHD INSTABILITIES IN TOROIDAL PLASMAS WITH D-CROSS SECTIONS

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The resistive MHD stability code RIPPLE VI is used to study numerically generated equilibria that model the proposed DIII upgrade (Big Dee) experiment at General Atomic. The equilibrium is two-dimensional, $\vec{B}_0 = \vec{B}_0(r,z)$, and contains poloidal and toroidal components.

Our numerical model assumes incompressibility and includes resistivity. We normalize the equations to the Alfven time and obtain a magnetic Reynolds number. We define a two-dimensional resistivity $\eta \sim p^{-3/2}$ where p is the equilibrium pressure. The perturbations vary as $f_1(r,z,t)\ \exp(in\theta)$ and we present results for $n = 1$.

The numerical domain consists of a rectangle. The dee-shaped equilibrium plasma is insulated from the walls by a vacuum region. The MHD equations are solved in the plasma region while the vacuum is treated differently. Since $p \to 0$ at the interface, we truncate η at some large value just inside the plasma and set η equal to a larger constant outside. In the vacuum the perturbations of magnetic field diffuse at a fast rate while the velocity terms are damped.

Results are presented for several equilibria and various Reynolds numbers.

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A 3D Alternating Dimension Equilibrium
and Transport Code for EBT*

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A three-dimensional alternating dimension equilibrium and transport code for toroidal systems with closed field lines and no rotational transform is being developed. The code is based on the alternating dimension algorithm developed at New York University.

In operation, equilibrium in the Elmo Bumpy Torus is achieved by a dynamic blanace between the electron annuli and the toroidal core plasma. The sensitivity of this balance to changes in the ring parameters is a measure of the flexibility of EBT experimental operation. The changes in the equilibrium resulting from variations in the ring position, ring beta and the number of rings will be presented.

The EBT core plasma is heated both by energy exchange with the electron ring and by direct radio-frequency heating. Preliminary results describing how these heating processes alter the equilibrium in the presence of Braginskii transport also will be discussed.

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ION CYCLOTRON HEATING OF AN EBT PLASMA

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Electromagnetic, fully self-consistent particle simulation of ion cyclotron heating of Elmo bumpy torus (EBT) plasma has been carried out. In order to accomodate relevant wavelengths in a manageable memory, we take a quarter of a multiple mirror plasma (mirror ratio ∿1.4) with an appropriate symmetry dependent on the parity of the EM fields in a two-and-one-half dimension code; we use a particle boundary condition that minimizes unwanted diamagnetic effects. In a two-species case (deuterium-proton), an external current perpendicular to the static magnetic field excites fast Alfven waves and, at the ion-ion hybrid resonance, they are partially converted to thermal modes which will eventually damp near the proton cyclotron resonance. Results of our simulation for a 10% proton concentration show that: (1) The fast waves mainly propagate from the strong mirror field side of the hybrid layer. (2) The perpendicular temperature of the minority most rapidly increases linearly in time. (3) The majority perpendicular temperature as well as the minority parallel one also increase. The former seems due to the second harmonic heating, since $(k_\perp \rho_i)^2 \sim 0.1$ and the observed heating is proportional to the ion temperature. (4) No appreciable electron heating is observed. For an increased deuterium concentration and/or mirror ratio, the heating rate decreases accordingly, because the narrower hybrid layer permits easier tunnelling for the fast waves.

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UCRL-85638

ANISOTROPY-DRIVEN INSTABILITIES IN MIRROR EXPERIMENTS*

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ABSTRACT

In the Tandem Mirror Experiment (TMX) at Livermore probes measured the characteristics of an instability that often arose in the end cells (plugs) and degraded central-cell confinement. These characteristics (frequency, wavelengths, and polarization) all appear consistent with theory of the Alfvén-ion-cyclotron (AIC) instability, an electromagnetic instability driven by temperature anisotropy of the ions. These measurements led to significant shifts in theoretical emphasis towards anisotropy-driven instabilities and away from modes like the drift-cyclotron loss-cone instability.

Our work attempts to construct a model based on AIC instability and compare it with TMX data. One striking observation is that the end-cell instability is strongly suppressed as the ratio of central-cell to end-cell density is increased. We understand this observation qualitatively in terms of cyclotron damping by ions of energy ~ 1 keV. These ions, in our model, originate in the central cell and are trapped and heated in the end cell by AIC instability. This scenario appears consistent with the measured energy distribution of end-loss ions.

Anisotropy-driven electron instabilities may affect future experiments, like TMX Upgrade and MFTF-B at Livermore, that require hot-electron populations. Of particular concern is the whistler instability, which is analogous to the AIC instability and which has been the subject of considerable experimental and theoretical work. If whistler instability occurs in TMX Upgrade, it degrades the efficiency of electron-cyclotron-resonance heating (ECRH) in producing hot-electron density.

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2B49

Abstract for Sherwood Meeting

Turbulence and Self-Consistent Fields in Plasmas

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Recently dramatic progress has been made in understanding the nonlinear dynamics of a single charged particle in a prescribed electromagnetic field. This had led to a notion of thresholds for chaotic motion resulting from resonance overlap and manifesting exponential divergence of initially nearby trajectories. For some imposed field models characterized by many discrete modes with uncorrelated phases, whose numerical solutions in the chaotic regime exhibit diffusion in velocity (action), there is an equivalence, in a well-defined parameter regime, between a single realization and the usual quasilinear theory which involves the ensemble average over many realization of the phases. This imposed field statistical theory also predicts (in the quasilinear limit) an exponential rate of divergence of initially nearby orbits (Kolmogorov entropy) which is in good agreement with numerical solutions of these uncorrelated phase, imposed field models.

Recent self-consistent computer simulations in this parameter regime are not in agreement with this familiar quasilinear theory. The self-consistent Maxwell's equations impose phase relations between modes and result in nongaussian statistics for the electromagnetic fluctuations. We show that the familiar random phase imposed field statistical theories cannot be made self-consistent (as is often assumed) by imposing Maxwell's equations a' posteriori on mean square fields and charge and current densities since these theories explicitly neglect intrinsic nonguassian correlations. The statistical closure scheme known as the direct interaction approximation, when applied to the self-consistent Vlasov equations, provides an explicit representation in which to treat these nongaussian correlations. In comparing this self-consistent theory with the quasilinear theory we find that new polarization terms arise which appear to significantly alter the predictions of quasilinear theory.

COLLISIONAL DRIFT WAVES IN THE SPHEROMAK GEOMETRY*

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We present an eigenmode analysis of electrostatic drift waves in axisymmetric spheromak geometry. The equilibrium is determined self-consistently[1] by numerically solving the Grad-Shafranov equation for an arbitrary aspect ratio spheromak. In the perturbation analysis, ions are treated as a cold fluid and the electron response is calculated from fluid theory, in the limit $\nu_{ei} >> |\omega|$, with ν_{ei} and ω being the electron-ion collision frequency and the mode frequency. The full self-consistent electron current dynamics are retained, and the relevance of current driven modes is assessed. For simplicity, a large toroidal mode numbers is assumed, and the ballooning mode representation is used.

*Work supported by the Department of Energy.

[1]The equilibrium is computed using the computer code ASSYST kindly provided by L. Sparks of Cornell University.

ON THE FRACTAL DIMENSION OF POWER SPECTRA*

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A general argument is presented concerning the fractal (Hausdorff-Besicovitch) dimension of the set of frequencies in the power spectrum of a system of N coupled oscillators. The theory thus explains the results of a recent numerical analysis of both the power spectrum of the Sun and laboratory spectra of hydrodynamic turbulence.[1]

The mathematical reasoning applies to a spatially-nonuniform collection of weakly-coupled nonlinear oscillators and relies upon the celebrated Kolmogorov-Arnol'd-Moser (KAM) Theorem[2] concerning the perturbation of Hamiltonian systems and the finite measure of the set of destroyed tori in phase space. This finite measure can be related to Hausdorff dimension by certain mathematical theorems.[3]

One consequence of these results is a simple empirical test for the applicability of Hamiltonian perturbation theory in the analysis of an experimentally observed spectrum; conversely, an absence of fractality would imply that either dissipation or strong nonlinear effects are important. If one's predilection is to employ a Lie-transform formulation to analyze perturbed Hamiltonian systems,[4] then this fractal criterion might be aptly termed a " Lie detector test ".

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HIGH BETA TAYLOR EQUILIBRIUM

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ABSTRACT

The plasma equilibrium which minimizes the magnetic field energy with the constraint that the magnetic helicity remains constant is force free.[1,2] Tayler[2] successfully used this concept to explain the stable regime of Zeta.

Recent compact tori are designed using this concept. However the force-free equilibrium does not allow a pressure gradient hence the plasma beta should either be zero or the plasma should have no boundary. The variation which leads to the Taylor equilibrium is given by

$$\int \delta \mathbf{A} \cdot (\nabla \times \mathbf{B} - \lambda \mathbf{B}) dV = 0$$

where A is the vector potential, B is the magnetic flux density and λ is the Lagrange multiplier. The force free equilibrium is the consequence of $\nabla \times \mathbf{B} - \lambda \mathbf{B} = 0$ since $\delta \mathbf{A}$ is in general not zero.

Now, consider a plasma with a sharp boundary. If the total flux in the plasma is conserved, the value of the vector potential at the plasma surface remains constant. This means $\delta \mathbf{A} = 0$ at the surface, hence at the boundary $\nabla \times \mathbf{B} - \lambda \mathbf{B}$ can take any value, yet the field satisfies the variational principle. Hence a surface current $\mathbf{J}_s$ perpendicular to $\mathbf{B}$ may be introduced there such that $\mathbf{J}_s \times \mathbf{B} = \nabla p$. The vacuum region then has a magnetic field produced by the wall current which runs in the direction opposite to the surface current. An example of such an equilibrium for a cylindrical plasma is presented. The plasma beta can assume an any value between zero and infinity depending on the magnitude of the wall current.

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A New Diagnostic for q(r) In Tokamaks: Alfvén Wave Resonant Absorption

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The location of the mode conversion layer, where $\omega = k_{\parallel} v_A = R^{-1}[\ell - m/q(r)]B_0[\mu_0 n(r) m_i]^{-\frac{1}{2}}$ for driven Alfvén waves, can be used to define the local safety factor q(r) or, equivalently, the poloidal field $B_p(r)$ in a tokamak. Calculations are presented to show that density fluctuations associated with the mode conversion are sharply peaked at the resonance layer. The density fluctuations may be detected with a small angle CO_2 or FIR laser scattering experiment. Preliminary results indicate that the fluctuations are well above the minimum detectable level with a kW input power and should be larger than the intrinsic fluctuation levels found in the plasma. The advantages and disadvantages of the method are discussed and the effects of toroidicity are indicated.

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Place adjacent to Chen, et al. (and Ross, et al. if poster).

Plasma Heating Using Axisymmetric (ℓ=0) Alfvén Waves

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Recent work on kinetic theory of Alfvén wave heating[1] has shown that the plasma resistance Z_R, (which is a figure of merit for the effectiveness of plasma heating) is, typically, very small, of the order of a few tenths of an Ohm. This would cast doubt on the practicality of this method for heating tokamak plasmas. For typical PRETEXT parameters, however, a notable exception is the axisymmetric (ℓ=0) mode, first studied by Perkins and Karney[2], for which sufficiently large $Z \approx 5\text{-}10$ Ohms may be obtained. For this mode, the local Alfvén frequency $k_{\|} v_A = [m/q(r)R] v_A$, determined by the radial variation of the safety factor (magnetic shear) and the plasma density, has a minimum, implying a double resonance for some range of frequencies. Whereas Perkins and Karney found the energy deposition to be divided roughly equally between the two layers, we find that, owing to kinetic effects, the energy is preferentially absorbed at the inner layer. Thus, an axisymmetric antenna could be used to excite Alfven waves which effectively heat the plasma interior.

This work is supported by DOE Contract DE-AC05-76ET 53036.

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TRANSPORT MODELING OF IMPURITY CONTROL BY DIRECT MOMENTUM AND INERTIAL EFFECTS*

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The unidirectional momentum input due to beams has been shown to affect impurity transport in tokamaks in two distinct ways. One is due to the direct effect on the momentum balance[1] of the beam source, the other due to the centrifugal effect of the ensuing plasma rotation.[2] Rough zero dimensional analytic criteria are known for impurity flux reversal by each method separately and with respect to each other.[3]

In this paper, a 1-1/2-D transport code with appropriate recycling boundary conditions is used to model both effects, in an ISX-B like plasma. The background plasma is modeled comprehensively (i.e. including beam deposition and anomalous electron transport), but impurity transport is restricted to neoclassical theory. Rather than assuming a specific momentum drag mechanism, impurity reversal is studied as a function of the drag frequencies.

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

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- POSTER SESSION

UCRL-85643

BETA LIMITATIONS IN SPHEROMAK AND RFM CONFIGURATIONS

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ABSTRACT

MHD Stability calculations for Spheromak and RFM geometries indicate that $n = 1$ current-driven modes and $n \rightarrow \infty$ pressure-driven modes present clear limitations for plasma parameters[1]. However, by properly shaping the plasma cross section[1], including a properly located conducting wall[1], and considering kinetic effects[2] outside the range of ideal MHD suggest that the effects of these modes can be ameliorated. The $n = 2$ mode appears to be the limiting factor for attaining higher beta's. This mode is in general not sufficiently localized to invoke kinetic effects such as FLR stabilization and since its driving energy comes from the central region of the discharge, wall stabilization appears very difficult. Results of a numerical investigation of this mode, including effects of pressure gradient, density gradient, and conducting wall, are presented.

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POSTER SESSION

Collisionless EBT Transport and Poloidal Electric Field

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ABSTRACT

We examine the collisionless EBT transport where the ion frequency ν_i is much smaller than the typical precession frequency Ω_o, using Fokker-Planck collision terms. In the plateau regime we found the poloidal electric field $\phi_1 = \phi_c \cos\theta + \phi_s \sin\theta$, where θ is the poloidal angle and ϕ_c and ϕ_s are of the same magnitude. The contribution of ϕ_c and ϕ_s to the particle and energy fluxes are found to be comparable to that of the curvature and gradient drifts.

The more sophisticated case of banana regime is also investigated.

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INHOMOGENEITY EFFECTS ON ICRF WAVES IN EBT-S

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EBT-S contains a highly inhomogeneous plasma in which both parallel and perpendicular scale lengths ($L_{\parallel}$ and $L_{\perp}$) are comparable in magnitude to the ion skin depth, c/ω_{pi}. Consequently, an analysis of ICRF waves in EBT-S cannot accurately make use of $c/\omega_{pi} L_{\parallel,\perp} \ll 1$ expansions. Even in the cold plasma approximation, both parallel and perpendicular derivatives of dielectrics play a significant role in the dispersion relation. The inhomogeneous dispersion relation has three implications for EBT-S: 1) Infinite and homogeneous fast and slow modes are coupled by inhomogeneity, suggesting that fast wave excitation based on weakly inhomogeneous theory could lead to fundamental ion-cyclotron heating in a single ion species EBT-S plasma. 2) The two-ion hybrid mode has an electromagnetic character in the cold plasma analysis. This property of two-ion hybrid modes in EBT-S impacts the possibility of mode conversion. 3) It is demonstrated in a model of EBT-S that finite electron inertia plays an important role in the analysis of ICRF eigenmodes.

Calculation of the Statistical Properties of Turbulent Dynamical Systems

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A path integral method is developed for the calculation of the statistical properties of turbulent dynamical systems. The method is applicable both to dissipative systems which exhibit strange attractors and to conservative systems which exhibit a transition to stochasticity. Explicit results are derived for the low order statistical moments for a variety of dissipative mappings including a model for the motion of a Brownian particle in a wave field with broad spectrum. In the nondissipative limit this model reduces to the Chirikov-Taylor mapping and the turbulent diffusion coefficient derived by Rechester and White[1] is recovered. The results in the collisional case show explicitly the effects of dissipation on the turbulent dynamics. Applications of these results to problems in stochastic wave heating are discussed.

This work was supported by the United States Department of Energy Contract No. DE-AC02-76-CH03073 and U.S. AFOSR Contract No. PR # 80-00656.

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ON THE EXISTENCE OF SLIT AND VERY RECTANGULAR EQUILIBRIA IN REVERSED FIELD THETA PINCHES*

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MHD Stability theory suggests that reversed field theta pinch equilibria are more stable if the flux surfaces are more rectangular in shape. Consequently, equilibria of this type have been sought. In one such configuration, proposed recently, the vortex point is extended axially to make a finite length slit and the flux surfaces near the separatrix are quite rectangular. Others also have been developed with this rectangular property but only have very elongated elliptical flux surfaces near the vortex. We review some of the existence theorems of partial differential equation analysis and from the continuum limit of the difference system representing the slit problem we show that the Cauchy boundary data inherent to slit configurations is problematic. Analytical examples of very rectangular equilibria sans slits will be presented.

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Low Frequency Electromagnetic Trapped Particle Modes In A Toroidal Plasma*

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An analysis of a finite beta, electromagnetic trapped particle mode is presented. It is assumed that the plasma is stable to modes which grow on an Alfvén time scale; the possibility of an instability whose growth rate is on the order of the particle drift frequency is then examined with a suitable variational form. This variational form is constructed from the zero Larmor radius limit of the kinetic equations appropriate for low frequency, short perpendicular wave length, electromagnetic modes in an arbitrary confining geometry.(1) The variational form is shown to give a sufficient condition for instability.(2) A numerical examination of this stability principle is then presented. This reveals a resonant, electromagnetic, kinetic mode, driven unstable by the vanishing of the bounce averaged drift of deeply trapped particles. Lower bounds for the growth rate of this mode are presented and shown to be only a few percent of the particle drift frequency.

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†Currently on leave of absence at the Laboratory for Plasma and Fusion Energy Studies, University of Maryland.

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POSTER SESSION

QUASILINEAR THEORY OF ICRF CURRENT DRIVE*

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ABSTRACT

Steady-state current driven by RF is of great interest in tokamaks. A scheme recently proposed by N. Fisch[1] consists of preferentially heating a minority ion specie in one direction by fast waves. In the present work, we formulate the quasilinear theory of the hybrid ICRF heating scheme, taking into account the characteristic localization of the left-hand component of the wavefield. The quasilinear Fokker-Planck equation is solved in tokamak geometry. Special care is taken to conserve energy and momentum in the models of collision operators used for different species. An analytical expression for current generation is obtained in the weak RF limit. We find a reduction in current generation due to trapped particle effects. Numerical results will be presented. We shall also discuss the launching structure for current drive purposes and the interrelation of density profile and the coupled spectrum.

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*Work supported by the Department of Energy, Contract DE-AT03-76ET51011.

THE EFFECT OF BUNDLE DIVERTORS ON MAGNETIC ISLANDS IN TOKAMAKS

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Bundle divertors affect both the magnetic ripple and magnetic islands in tokamaks. The effect on magnetic ripple can be reasonably accurately determined by considering just the vacuum field from the divertor. For the effect on low-order magnetic islands, however, it is necessary to consider the perturbation of the plasma currents in response to the islands. We have developed a self-consistent technique[1] to determine the widths of many magnetic islands simultaneously from saturated tearing modes together with externally applied magnetic perturbations. It is found that naturally occuring saturated tearing modes tend to enhance only the low-order magnetic islands that are produced by the applied perturbation. Tearing modes have little direct effect on high-order magnetic islands near the edge of the plasma. However, these magnetic islands have a strong effect on the current profile since the current density is locally flattened in the neighborhood of each magnetic island. The overall current profile is flattened near the edge of the plasma, where the effect of the applied perturbation is strongest, and consequently more peaked near the center of the plasma. This change in the current profile must be limited in order to avoid greatly enhancing low-order saturated tearing modes and precipitating a disruptive instability.

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ION CYCLOTRON RESONANCE HEATING AND ITS EFFECT ON CONFINEMENT IN TOKAMAKS*

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The effect of ICRF heating on confinement in tokamaks is studied using single particle equations of motion in a "quasi-adiabatic approximation" (conservation of magnetic moment, angular momentum and energy between resonances). A set of mapping equations for μ, P_ϕ and W is used to follow the particle motion for times long compared to the period of the trapped or passing particles. The threshold r.f. electric field amplitude for the transition from the superadiabatic to the stochastic regime is found to be well below the value used in present day experiments like PLT and Macrotor. The effect of heating on confinement in absence of collisions is examined by studying the change in single particle orbits produced by the r.f. The formalism is extended to include the effects of collisions on the fundamental heating of a minority ion species in a multi-ion species plasma. Minority ions are regarded as test particles moving through a background medium composed of majority ions and electrons, collisional effects being treated by a Monte-Carlo method. By following an ensemble of ions, the evolution of the velocity distribution function in $v_\parallel$ and $v_\perp$ and of the line density of the minority ions is found and compared with the collisionless results. The trapping rate, the loss rate and the energy transferred to the background plasma through collisions are also calculated using parameter values appropriate for current Macrotor and PLT experiments.

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COMPUTER SIMULATION OF LOWER-HYBRID HEATING IN TOKAMAKS *

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A simple quasilinear model of lower hybrid heating and current drive has been added to the PPPL BALDUR 1-D tokamak transport code.[1] Electron heating and current terms were calculated from Fisch's theory.[2] We assumed that the local distribution function had a "quasilinear plateau" such that the wave energy absorbed via quasilinear Landau damping in the resonant region was balanced by collisional transfer to the bulk of the electrons. A spectrum of RF waves, typically 30 "modes" in our simulations, was launched at the edge. As each mode travelled inward, the local electron energy absorption and current terms were calculated. Electron absorption continued until the mode was completely attenuated or until the linear mode conversion layer was reached. At this point we assumed that the wave undergoes linear mode conversion and that the remaining energy was absorbed by the ions within a BALDUR radial zone width (typically 1-2 cm. for PLT). We used cylindrical geometry in calculating the absorption terms, such that $n_{\parallel}$ was constant, but the wave energy focussed due to the radial dependence of the group velocity.

The code was applied to PLT and to a proposed reactor design. It was found that quasilinear theory implies better wave penetration than linear theory,[3] since electron Landau damping losses are reduced in the outer parts of the plasma and that restrictions on RF input spectra for reactors are less stringent.

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POSTER SESSION

ANOMALOUS TRANSPORT IN A TOKAMAK WITH LARGE FLOW VELOCITY*

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ABSTRACT

Experimental results in the beam-driven PLT tokamak show toroidal rotation of the plasma in the low 10^7 cm/s range. The toroidal viscosity is estimated to be of the order of 10^4 cm^2/s and the diffusion coefficient of the argon species about 6×10^3 cm^2/s. Both of these numbers are much higher than the neoclassical predictions. Possible anomalous mechanisms are discussed using a quasilinear formalism. The toroidal momentum damping is postulated to be due to the shear in the toroidal rotation velocity and the heavy impurity transport to be due to the equilibrium radial electric field. It is found that the radial magnetic fluctuation level of order 10^{-4} is sufficient to yield transport of both toroidal momentum and impurity particles in the observed rate. Furthermore, the direction of such radial impurity flow is in agreement with the experimental observations on PLT and ISX-B tokamaks.

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FAST MOMENT EQUATION METHOD FOR SOLVING THE GRAD SHAFRANOV EQUATION*

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A set of nested toroidal plasma surfaces can be represented by expressions of the form

$$R = \sum_{n=0}^{\infty} R_n(\psi)\cos n\theta \quad , \qquad Z = \sum_{n=1}^{\infty} Z_n(\psi)\sin n\theta \quad ,$$

where ψ is the poloidal flux function. It is found that with a good choice of poloidal angle θ, only a few harmonics are required. For an elliptical plasma, (R_0,R_1,Z_1) are sufficient and for a D shaped plasma going to the third harmonic is adequate.

Several methods exist for determining the harmonics; one is straight forward insertion into the Grad Shafranov equation. Another fast method is to use a variational principle to obtain a set of coupled, second order, ordinary differential equations for the amplitude.[1] A still faster method is to obtain a set of moment equations by a weighted integration of the Grad-Shafranov equation from the magnetic axis to an arbitrary contour. The integral is zero; i.e:

$$\int_0^{\psi} d\psi' \oint d\theta G(R,Z)\left[\Delta^* \psi' + 4\pi R^2 \frac{dp}{d\psi'} + f\,\frac{df}{d\psi'}\right] = 0, \ \ldots \tag{1}$$

where (R,Z) are functions of ψ' and θ, and (p,f) depend only on ψ'. Two integrations by parts alter the integral so that the Δ^* operator is applied to G rather than ψ. In general a surface term arises in the process which contains in the denominator J, the Jacobian of the transformation from (R,Z) to (ψ,θ) coordinates. The variational method also has a term containing J in the denominator. For finite beta plasmas there is a large variation in J with θ which leads to serious difficulties for analytical work, and time consuming θ integrations for numerical methods.

A set of G functions for Eq. (1) can be found which eliminates the surface term. The result is a set of moment equations which depend on the (R_n,Z_n) amplitudes, but not on any of their derivatives, and on another set of functions $H_j(\psi)$ whose derivatives with respect to ψ depend again only on the (R_n,Z_n) amplitudes.

This formulation eliminates the need for any numerical θ integration. It also simplifies analytical work since there are known representations for the amplitudes that are poor for their derivatives.

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Numerical Simulation of Transport in Tokamaks with Ripple

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ABSTRACT

Development of a code to compute transport in non axisymmetric plasma is continuing.[1] The code uses the alternating dimension algorithm whereby 1-D flux-averaged equations are marched in time by a set of diffusion equations.[2] The geometric coefficients required for these equations are computed by periodic calls to the Bauer, Betancourt, Garabedian (BBG) equilibrium solver.[3] The 1-D transport and 3-D equilibrium are then alternated until the geometric coefficients converge.

The code has computed a converged solution for a tokamak with a 10% ripple. Numerical and graphical results for this case will be presented.

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Poster Session

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SINGULARITY (CATASTROPHE) THEORY AND IDEAL MHD*

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The structure of the equilibrium manifold for a tokamak in a parameter space which includes the second stable regime is reminiscent of an elementary catastrophe surface. In our modelling of the equilibrium of the high-beta tokamak Torus II, we have noticed that the existence of a singularity is indicated. The ideal MHD equations thus bear examination with the thought of finding standard forms (in analogy with the eleven catastrophe polynomials for systems with a finite number of degrees of freedom) for singular points in a system with an infinite number of degrees of freedom. A path to this necessary extension is presented. The Hamiltonian formulation of the ideal MHD equations[1] permits us to specify the equilibrium as a variational problem and enables us to envision performing a stability analysis in a canonically transformed coordinate system. In addition, the bifurcation theory for buckling columns[2] suggests the use of a generalized gradient operator for analyzing such spaces of infinite dimension. These methods are shown to be relevant to the investigation of equilibria determined by the ideal MHD equations.

Preliminary to the above discussion, we demonstrate the applicability of catastrophe theory to plasma physics by means of an elementary example: the structural resemblance of the plasma equilibrium to the 2n-roll mill in fluid dynamics.

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PRESSURE PROFILE EFFECTS ON BALLOONING MODE STABILITY*

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Without assuming stabilization through kinetic effects (i.e., finite n corrections [1]), MHD stability with respect to ballooning modes ($n = \infty$) is shown to improve with a careful choice of the pressure profile. We consider D-shaped equilibria with toroidal current density and pressure profiles going continuously to zero at the plasma edge and a prescribed safety factor profile $q(\psi)$. Using typical FED parameters ($R_0 = 4.8$ m, $a = 1.3$ m, $B_t = 3.6$ T, $q_{axis} = 1.0$, $q_{edge} = 2.7$, and elongation $\sigma = 1.6$) and exponential pressure profiles, a sequence of numerical equilibria with increasing beta is used to map a region of ballooning instability in the pressure derivative $(\frac{dP}{d\psi})$ and shear $(\frac{d\ell nq}{d\ell n\rho})$. We demonstrate that by constraining P' on flux surfaces of high shear and increasing |P'| for low shear, as suggested in [2], a pressure profile may be prescribed (using a B-spline series) such that this region is avoided to achieve relative increases in stable beta values. An example is found to be ballooning stable at $<\beta> = 5.5\%$ (the current design assumption for FED) as compared to a maximum stable beta value of about 3.8% using exponential profiles. Possible implications of these results in terms of the apparent discrepancy between the achieved and calculated ideal MHD stable $<\beta>$ values in ISX-B [3] are discussed.

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Eddy Currents in Conducting Shells due to Plasma Motion

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The stabilizing effect of conductors surrounding a plasma is due to the generation of eddy currents caused by the plasma motion. The calculation of the distribution of these currents in the conductors can be useful for designing conductors which are optimal for stabilization, and also for estimating the electromechanical stresses involved. It can also be a useful diagnostic tool for analyzing the plasma motions. We present calculations showing the eddy currents for both topologically toroidal (tokamak) and topologically spherical (spheromak) configurations.

Poster Session

THE EFFECTS OF SMALL AMPLITUDE MHD INSTABILITIES ON MAGNETIC FIELD TOPOLOGY*

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We present a numerical method used to study topology changes when instabilities are superimposed on equilibrium fields. Our tool is a modified version of the TUBE code [1] which follows magnetic field lines in cylindrical coordinates. The program accepts either toroidal or cylindrical geometries.

The equilibrium studied is the Bessel Function Model [2] where $\vec{B}_0 = B_{\theta 0}(r)\,\hat{\theta} + B_{z0}(r)\,\hat{z}$. We first compute two instabilities of differing helicities using a 1-D resistive MHD stability code RIPPLE IV [2] and superimpose small amounts of the modes on B_0. As the amplitude of the instabilities is increased we first see two magnetic islands; later the two islands overlap creating a stochastic annular region.

[1]. J. Killeen, H. P. Furth and R. P. Freis, LLNL report UCRL-50161 (1967).

[2]. J. A. Dibiase and J. Killeen, J. Comp. Phys. 24, 2(1977).

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Non-Resonant and Higher Order RF Current Drive*

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In the conventional RF current drive schemes, RF waves are absorbed by resonant particles and thence lead to current generation. Using concepts borrowed from parametric excitation theory, we give a preliminary investigation of two unconventional ways in which RF may be used to drive electron currents in a plasma. The methods discussed are: (a) the use of non-resonant ponderomotive forces in collisionless and collisional plasmas; (b) the use of stimulated backward scattering in which the absorbed RF wave is re-emitted by the electrons, thereby giving a possible improvement in the efficiency of current generation (i.e., amps./watt). Estimates of the optimal RF frequency and typical power requirements will be presented.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

Poster Session

1981 SHERWOOD THEORY MEETING
Austin, Texas - April 8-10, 1981

INFERENCE OF MAGNETIC FIELD PROFILES IN THE REVERSED FIELD PINCH*

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Knowledge of the field profiles in the RFP device can be used to make estimates of the plasma on-axis resistivity and the global energy confinement time, as well as for comparisons with the profile evolution predicted by transport codes. However, the plasma is degraded by the employment of extended multipoint magnetic field probes. Therefore, we investigate the degree to which meaningful field profile information can be obtained by combining known external measurements ($B_z(a)$, $B_\theta(a)$, Φ_z) with a minimal amount of internal information.

Expansions of the cylindrically symmetric fields in power series in the minor radius constitutes a simple and straightforward approach. By using the even/odd properties of the fields, together with low-beta pressure balance, power series representations through r^6 can be fully determined by the external measurements, and one internal measurement. A lower order series, ending at r^4 would not require the internal measurements. However, we find that such a series is usually unable to account for the external measurements. Good agreement with the r^6 series is thereby reached with multipoint probe measurements on ZT-40 with a ceramic liner. Series representations of both nonquiescent shot-averaged and quiescent profiles were obtained and, within the limitations inherent to this method, were found to be ideal and resistive MHD stable. It is to be noted that they differed significantly from the Taylor and Robinson profiles.

Extensions to include measured plasma pressure profiles in the method are straightforward, on the basis of laser interferometry for n(r), Thomson scattering for $T_e(r)$, and equipartition for T_i. It will also be shown that Faraday rotation is a sufficiently sensitive method to be used for the required internal magnetic measurement.

*Work performed under the auspices of the USDOE.

POSTER SESSION REQUESTED

SATURATION AND TRANSPORT BY THE LOWER HYBRID DRIFT INSTABILITY IN TWO DIMENSIONS*

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The nonlinear saturation of the lower hybrid drift (LHD) instability and associated particle transport is studied for a two dimensional wave spectrum (perpendicular to $\underset{\sim}{B}$). In previous 1-D calculations, it has been demonstrated that LHD can not irreversibly transport electrons across $\underset{\sim}{B}$ unless a rather large threshold $e\phi/T_i \sim (k_y \rho_{es})^{-2} \sim .25$ is exceeded.[1] In a two dimension wave spectrum, irreversible electron transport can take place when the $\underset{\sim}{E} \times \underset{\sim}{B}$ trapping threshold is exceeded, $e\phi/T_i > (k_x L_n)^{-1}$, x being the direction of inhomogeneity with scale length L_n. An unstable lower hybrid drift mode propagating along the diamagnetic drift direction y is found to decay into off angle modes with $k_x \sim k_y$ which saturate as they $\underset{\sim}{E} \times \underset{\sim}{B}$ trap the electrons. The original unstable mode saturates at an amplitude $e\phi/T_i \approx (m_e/m_i)^{1/2}$. The finite k_x decay modes therefore act as an intermediary which both transports electrons irreversibly and saturates the original instability.

*Work supported by the Office of Naval Research.

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[2]R. E. Aamondt, SAI Report #76-668-LJ; S. P. Hirshmann, Phys. Fluids 23, 562 (1980).

Particle Losses in Reversed Field Devices Due to Loss-Cone-Like Scattering*

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The loss mechanism due to ion-ion scattering into the loss-cone-like region in E-P_θ space in a Field-Reversed Theta Pinch (FRTP) is under study. Preliminary results give particle confinement times that agree within a factor of two with those of the experiments, FRX-A and -B,[1] suggesting that this mechanism may be an important process for particle losses in this geometry.

The loss-cone-like region in E-P_θ space stems from the absolute confinement criteria[2,3] which require $E \leq -P_\theta \omega$ for a particle to be axially confined, where E and P_θ are the particle total energy and the canonical angular momentum, respectively, and ω is the gyro-frequency at the magnetic end throat. Collisions between particles, including like-particles, can self-scatter out of the confinement region (through changes in E and/or P_θ) and be lost.

For simplicity, a cut-off rigid-rotor distribution is assumed, instead of solving the Fokker-Planck equation self-consistently. Using the parameters of FRX-B we calculate a $\tau_p \approx 105\mu s$. Furthermore, this model predicts a scaling of $\tau_p \propto T_i^{0.8} K^{1.2} R_w^{2.2}$, where T_i and R_w are the ion temperature and wall radius, respectively, and $K = -\tanh^{-1}[B(r=0)/B_\infty]$. In effect, the loss-cone-like scattering can be viewed as a "classical" upper limit for particle confinement in the FRTP or FRM-like configurations. Instabilities and anomalous losses may reduce the actual confinement below this bound in practice.

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Nonlinear Threshold of Toroidal Field for the Collisionless Tearing Instability

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A fully nonlinear collisionless tearing mode study by 2-1/2D electromagnetic particle simulation has been carried out. An initially uniform plasma in the xy plane is immersed in a uniform toroidal field (in z) with toroidal currents (in z) rising in time to reach a crowbar. These external currents are spatially fixed in sheets parallel to the direction. It is found that there exists a threshold for the ratio of the toroidal to the poloidal magnetic fields above which the field line tearing near the rational surface does not occur. With this ratio above the threshold, small-scale field rippling and slight (linear in time) heating of electrons and ions, but no significant tearing, are observed for both $\rho_i > \Delta_{linear}$ (the Laval regime) and $\rho_i < \Delta_{linear}$. With the toroidal to poloidal ratio below the threshold, a strong tearing instability sets in and magnetic islands are induced, followed by explosive island coalescence and formation of extremely hot bulk and tail ions. A preliminary theoretical explanation of the nonlinear threshold is advanced based on the electron convective nonlinearity in the parallel direction. The nonlinear growth rate may be calculated as $\gamma_{NL} \simeq (c/\omega_p)\ (\Delta'/L_S)\ k_y v_e$ and $\Delta_{NL} \simeq (c/\omega_p)\ (L_s/a)^{1/2}$. This instability has much wider island width Δ_{NL} than the linear theory by Drake and Lee. In our present simulation, the shear length L_s becomes effectively longer when the toroidal field is stronger, since the amount and location of toroidal currents are fixed, thus contributing to a lower growth rate. In addition, the larger nonlinear island width may make the growth of islands more difficult since the external current channels are fixed.

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Finite n Ballooning Modes with ERATO

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An eikonal transformation $\hat{\underline{\xi}} = \underline{\xi}^{e^{inq\chi}}$ has been introduced into our ideal MHD stability code ERATO.

For high shear equilibria the eigenmodes and eigenvalues can be calculated up to n = 100. For low shear equilibria, e.g. for the Solovev equilibria, we have to take up to 200 x 50 intervals to resolve the radial structure for $n \leqslant 20$.

With this eikonal transformation it is possible to handle all the physically meaningful values of n.

FUSION EFFICIENCY OF A DD TANDEM MIRROR REACTOR*

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The fusion efficiency of the solenoid of a tandem mirror reactor employing the catalyzed DD cycle is analyzed using the two-dimensional Fokker-Planck code HYBRID II. A two-dimensional nonlinear Fokker-Planck analysis is necessary to properly account for the escape of ions through the curved loss-cone boundary and to properly model the slowing down and scattering of the injected deuteron beams and high energy fusion products.

Fokker-Planck equations for each ion species (D, T, He^3, α, p) are solved in a square-well configuration. An improved finite-difference technique which more accurately models situations in which slowing down greatly exceeds scattering is implemented. The four relevant fusion reactions appear as source and loss terms. The plug to solenoid electron density ratio is assumed to be fixed.

The electrons are taken as Maxwellian, with a Pastukhov loss time. Bremsstrahlung and synchrotron radiation loss terms are included. An ambipolar potential consistent with quasi-neutrality is computed.

New results and comparison with previous work[(1)] are presented.

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2C31

LOW FREQUENCY ELECTROSTATIC DRIFT WAVES IN A PLASMA SHEATH*

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Low frequency drift waves are considered in a planar sheath of neutral plasma of thickness of order of the ion gyroradius. An integral eigenmode equation is derived and solved numerically using fast Fourier transforms. The analysis is valid for arbitrary wave numbers and accounts for shear in the equilibrium magnetic field. We find that unstable universal drift modes can exist in this strongly localized plasma. In contrast to what has been found previously in connection with weakly inhomogeneous plasmas, we observe here that shear can have a destabilizing influence. The relevance of this idealized model to experiments is also discussed.

*Work supported in part by the Department of Energy and the Office of Naval Research.

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SIMULATION STUDY OF THE CURRENT-DRIVEN ELECTROSTATIC ION CYCLOTRON INSTABILITY*

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Density fluctuations in the region of the ion cyclotron frequency and its harmonics have been observed in TFR.[1] We report the results of particle simulations of the current-driven electrostatic ion cyclotron instability. These simulations are initial-value calculations in which the driving mechanism for the instability is an initial drifting Maxwellian distribution for the electrons. With $T_e = T_i$, we find that ion cyclotron waves grow to moderate levels characterized by $e\phi/T_e \sim 0.2$-0.3 and $\delta n_{ion}/n_o \sim 0.05$-$0.07$. Saturation of the instability is found to be due to plateau formation on the electron distribution function. Moderate ($\sim$40%) perpendicular heating of the ions is observed, while the anomalous resistivity associated with the instability is very small, $\nu^*/\omega_{pe} \sim 1 \times 10^{-4}$. The effects of ion currents and nonequal electron and ion temperatures ($T_e > T_i$) are being investigated, and results will be discussed.

*Work supported by USDOE, NSF and NASA.

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Eddy Currents in Conducting Shells due to Plasma Motion*

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The stabilizing effect of conductors surrounding a plasma is due to the generation of eddy currents caused by the plasma motion. The calculation of the distribution of these currents in the conductors can be useful for designing conductors which are optimal for stabilization, and also for estimating the electromechanical stresses involved. It can also be a useful diagnostic tool for analyzing the plasma motions. We present calculations showing the eddy currents for both topologically toroidal (tokamak) and topologically spherical (spheromak) configurations.

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Poster Session

1981 SHERWOOD MEETING
ANNUAL CONTROLLED FUSION THEORY CONFERENCE

APRIL 8 - 10, 1981
THE UNIVERSITY OF TEXAS
AUSTIN, TEXAS

ICRF Heating by Ion Orbit Parametric Resonance

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ABSTRACT

We examine the motion of ions in a fast ion cyclotron wave ($E_z \approx 0$) at the second harmonic. The work is in contrast to [1] where an electrostatic mode was studied. The dynamics of the bulk ions in the transverse direction is governed approximately by a Mathieu equation. For reasonably large field amplitudes many particles will be unstable in the first resonant zone and their trajectories will exponentiate at a rate γ. This will lead to an appreciable damping of the wave and heating of the ions above a certain threshold, $\gamma > \nu_{ii}$. For Alcator parameters at power levels of 500 kW one has typically $E_x, E_y \simeq 100$ v/cm and $\gamma \simeq 10^{-3}\,\Omega_i$. We should emphasize that the damping of the wave by parametric resonance is nonlinear $\gamma \sim E_{\perp}$. Therefore, γ will be negligible at low power levels.

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POSTER SESSION

CURRENT DRIVE SCHEMES FOR TOKAMAK REACTORS*

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ABSTRACT

Since steady-state operation of a tokamak is likely to improve its prospects for success as a fusion reactor, driving a steady current is one of the key elements in such a device. Various schemes have been considered to drive such a current; these include different types of radio frequency (RF) waves and also the injection of energetic neutral beams. In an ignited tokamak using deuterium and tritium as fuel, the production of energetic alpha particles suggests the possibility of a novel source of current drive. In this paper, we explore the concept of current drive using alpha particles which are born isotropically in a tokamak. For the passing particles, one may achieve a condition that could be described as "induced anisotropy" by pushing these particles in a preferential direction (e.g., by means of a suitable RF wave) and thus form an alpha particle beam. As a result, a net plasma current may be generated.[1] For the magnetically trapped particles, the push from such RF waves would result in what may be termed as an "enhanced bootstrap" effect. Using parameters of an INTOR-type device, we consider the current generated through such a scheme and compare that with the steady-state current expected to be produced by other means. The presence of alpha particles mostly at the central hot core of the reactor indicates that the current profile is most likely to be peaked at the center.

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*Work supported by the Department of Energy, Contract DE-AT03-76ET51011.

POSTER SESSION

COIL OPTIMIZATION FOR ERGODIC MAGNETIC LIMITERS*

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ABSTRACT

The ergodic magnetic limiter (EML) has been proposed[1] to improve the power handling problem in tokamak reactors. External coils or ferromagnets would be used to produce overlapping islands near the boundary of the plasma creating a cold ergodic field region while leaving the central plasma undisturbed. Thermal energy would be distributed uniformly over the first wall by the ergodic field, thus reducing the heat load. With a simple equilibrium model, we have analyzed the effects of various coil configurations on the plasma equilibrium using Fourier analysis techniques. The Fourier analysis method provides an extremely fast way to determine which resonant surfaces will be driven by a given coil configuration without resorting to following field lines. Therefore a wide class of configurations can be evaluated and optimized. Toroidal effects are included. We have examined various coil configurations including helical windings and many window frame coil designs. By varying the shapes, spacings, and currents of window coils, two main neighboring helical components (for example $q = m/n = 6/3$ and $q = m/n = 5/3$ surfaces) can be produced with one simple set of coils. Normally, two helical windings with different winding laws would be needed to drive both the $q = 2$ and the $q = 1.66$ islands. To reduce the maintenance and accessibility problems, these coils are designed to cover the outside of the torus only. Window frame coil designs which provide additional controlling capabilities are definitely more desirable for experimental purposes than half-wound helical windings.

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*Work supported by the Department of Energy, Contract DE-AT03-76ET51011.

Stochastic Damping of an Obliquely Propagating Wave*

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The transition between regular and stochastic motion plays an important role in present-day theories of rf heating and anomalous electron transport. Most theoretical work on this transition has focused on single-particle motion in a fixed-amplitude wave. Since many experiments and simulations look primarily at waves and not individual particles, it is important also to determine what effect the onset of stochasticity has on wave evolution. We explore here the self-consistent evolution of an obliquely propagating Langmuir wave. Particle motion will be stochastic when the resonances located at $v_{\parallel} = (\omega - n\Omega)/k_{\parallel}$ overlap and regular when they do not.[1] Assuming that in the asymptotic state($t\to\infty$) the distribution function is flattened over the resonant regions (or over two or more resonant regions when they overlap) we find that the total damping of the wave significantly increases when a transition is made between the regular and stochastic regimes. In the regular regime, a method similar to O'Neil's[2] has been used to determine the time-development of the wave amplitude. In both regimes, the temporal evolution of the wave amplitude and of the particle velocity distribution have been studied using a mini-simulation in which particles in the region of phase space strongly affected by the wave are followed numerically. The predicted increase in total damping with increasing resonance overlap is observed.

*Supported by USDOE and NSF.
+Supported in part by the Fannie & John Hertz Foundation.

1. G. R. Smith and A. N. Kaufman, Phys. Fluids, 21, 2230 (1978).
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1981 SHERWOOD THEORY MEETING
Austin, Texas - April 8-10, 1981

IDEAL AND RESISTIVE MHD STABLE STARTUP FOR THE REVERSED-FIELD PINCH REACTOR*

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Previous work[1] on an ideal MHD stable convective startup technique (pitch convection[2]) for the RFP has been extended to include resistive modes. A startup scenario has been found that is effectively stable to resistive and ideal modes. Effective stability is defined as stability to those modes with e-folding times shorter than the startup time. Growth rates are calculated by the Hewett-Freidberg matrix shooting code[3] while transport is simulated by the RFP burn code (RFPBRN).[4]

Results indicate that effective stability can be maintained during startup provided the proper aspect ratio and field programming procedures are chosen. Sensitivity to the programming procedure and startup time are discussed.

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POSTER SESSION REQUESTED

Scaling of the Electron Energy Confinement Time*

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The scaling of the electron energy confinement time, derived[1,2] from an expression for the electron thermal diffusion coefficient, is tested on a large number of FT[3] and Alcator C[4] discharges covering a wide range of parameters, such as, $0.4 \le \bar{n}_e(10^{14}) \le 6$ and $3 \le q_s \le 6$. The scaling, represented by the variable

$$\tau_1(\mathrm{ms}) = 1.28 \langle n_e(10^{14}) T_e(\mathrm{keV})\rangle \frac{a^3(\mathrm{cm}^3)}{I_p(\mathrm{kA})} \left[\frac{A_i}{n_o(10^{14}) Z^2_{eff*}} \right]^{1/5} ,$$

has been expressed[5] in an equivalent form in terms of experimental input parameters

$$\tau_2(\mathrm{ms}) = 0.107\, \bar{n}_e(10^{14}) a^2(\mathrm{cm}^2) \left[\frac{A_i\, q_o \quad R/a}{n_o(10^{14}) B_T(\mathrm{kG}) G^2} \right]^{1/3} \left(1 - \frac{3}{2}\frac{q_o}{q_s}\right) F ,$$

where A_i is the ion mass number, q_s the safety factor at the limiter, and $F(q_s/q_o) \simeq 1$. The electron-ion power transfer is taken into account by including the factor $G = (1 + P_{ei}/P_e)$, and multiplying the experimental electron energy replacement time by $(1-P_{ei}/P_{OH})^{-1}$. Here the volume-integrated terms P_{OH}, P_{ei}, and P_e (from the electron energy balance equation) are evaluated at $r/a = 2/3$.

The results indicate that both sets of discharges from Alcator C and FT are well represented by this scaling. The consequences of combining the scaling above with that of the collisional ion energy confinement time will be discussed. In particular, in the regimes where the ion energy losses begin to play role, the total energy confinement time exhibits an optimum as a function of the plasma current when the density is kept roughly constant.

*Supported in part by the United States Department of Energy.

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A STEADY-STATE SPHEROMAK MAINTAINED BY COALESCENCE*

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It has been observed experimentally that two spheromaks can coalesce on a time scale short compared to their resistive decay time.[1] We have studied the feasibility of maintaining a spheromak in steady state by repeated coalescence with smaller spheromaks. The quasi-ideal model[2,3] has been used to describe the reconnection process. We first assume that the process is purely axisymmetric, and determine afterwards how the picture is affected by the presence of nonaxisymmetric tearing modes.

Assuming axisymmetry, the required q profile for the refueling spheromak is determined by the fact that the q's of corresponding flux surfaces add during reconnection. Eliminating $I(\psi)$ from the Grad-Shafranov equation in terms of the known $q(\psi)$, we obtain a QDE[2] which determines the equilibrium. We solve the equation analytically in the large aspect ratio limit (i.e. large flux hole), and use the solution to get an estimate of the efficiency of maintaining a steady state spheromak in this way.

Nonaxisymmetric tearing modes provide a mechanism for increasing the poloidal flux. This allows us to improve the efficiency of our refueling process, but only at the expense of introducing large scale turbulence into the fusion plasma. To treat the effect of a single such mode, we use the conservation of toroidal flux within each helical flux surface.[3] In the presence of a number of such modes of different helicity, we expect that only the total toroidal flux and total magnetic helicity will be conserved,[4] allowing us to apply Taylor's theory of magnetic field relaxation.[5,6]

We have, finally, also shown that coalescence may be an effective means of heating a cold spheromak plasma, and can also provide a valuable method for experimentally studying magnetic field relaxation.

*Research supported by the Office of Naval Research.

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MAGNETIC SPECTRA OF CURRENT CARRYING MEDIA

by

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The zero frequency magnetostatic mode has been discussed previously for a magnetized plasma in thermal equilibrium.[1] Here a similar zero frequency magnetic structure is considered for current carrying media. Since these structures are the natural collective responses, it is expected that they will play a crucial role in plasma confinement. The special case of force-free fields $\nabla \times \vec{B} = \mu\vec{B}$ with constant μ belongs to this class. By capitalizing on the constancy of magnetic helicity $H = \int \vec{A}\cdot\vec{B}\, dv$, a statistical theory is developed to obtain the wavevector $\vec{k}$ spectrum. Dictated by the boundary conditions, the long wavelength (comparable to the dimension of confinement device) spectra are usually quite anisotropic. As a consequence, large scale helical structures may appear. On the other hand, the short wavelength spectra are isotropic and scale universally like $k^3 e^{-k/k_o}$ with k_o a constant characterizing the "magnetic temperature" of the medium. Transport due to these short wavelength structures is estimated from strong turbulence theory as $D \simeq 1/3 \left(\frac{c}{\omega_p}\right)^2 \tilde{\Omega}$ where $\tilde{\Omega}$ is the cyclotron frequency in the root mean square total short wavelength magnetic fields. The density dependence of D is like Alcator scaling (n^{-1}).

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THEORY OF NON-LINEAR ION–ELECTRON INSTABILITY

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A non-linear theory describing the regeneration of clumps[1] in a two species plasma is presented. A self-sustaining state exists when the decay of these fluctuations due to ballistic streaming and the turbulent electric fields (for example in the form of velocty diffusion), is balanced by the creation of new ones through the mixing of the average gradients. The self-sustaining condition can also be regarded as a stability boundary, since over-regeneration implies that the system will be unstable to these modes.

Our equations are a simplified version of the renormalization developed in Ref. 2. They retain the following important features:

(i) The singular behavior inherent to the two-point equation is incorporated through the clump spectrum.

(ii) A self-consistent formulation is used to describe the shielded test-clump picture.

Numerical and analytical solutions of these equations, for an ion–electron plasma, in the presence of a drift (v_d) of the average electron distribution predict that the spectrum of fluctuations is unstable to drift velocities which are appreciably below those required for the onset of linear instability (typically a 50% reduction in the required drift). The characteristic signature of these modes is the growth rate which is amplitude dependent, being inversely proportional to the trapping time. These results are in good agreement with a numerical simulation presented concurrently at this meeting[3].

While we treat the more tractable current driven ion-acoustic regime, this type of analysis is general and can be extended to more complicated geometries which include density gradients and magnetic shear.

This work is supported by the National Science Foundation and Department of Energy.

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POSTER SESSION

FINITE-n BALLOONING MODE THEORY FOR AXIALLY SYMMETRIC TOROIDAL PLASMAS*

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ABSTRACT

Ballooning mode theory for finite toroidal mode number is extended to include axisymmetric plasmas where the flux-averaged shear vanishes. Tokamaks with shear free regions, or toroidal multipoles with closed field lines are examples of such plasmas. The effect of compressibility is demonstrably stabilizing for finite toroidal mode number. The critical mode number, below which the plasma is stable, is correctly calculated from the same EBK theory[1] used for tokamaks.

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*Work supported by the Department of Energy, Contract DE-AT03-76ET51011.

1981 SHERWOOD THEORY MEETING

Austin, Texas - April 8-9, 1981

KINETIC THEORY OF DRIVEN RECONNECTION AT AN X POINT*

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A kinetic model is developed for plasma flow in the fields $\underset{\sim}{B} = B'(x\hat{y} + y\hat{x})$ and $\underset{\sim}{E} = E_o\hat{z}$. Particle motion is treated analytically away from the X point where the magnetic moment is an adiabatic invariant. A particle pushing code describes ion and electron motion near the X point where adiabaticity breaks down. Plasma flowing toward the separatrix is Maxwellian. In the absence of collisions and resistivity, particles moving close to the X point still may gain or lose kinetic energy due to the breakdown of adiabatic invariants. Plasma moving away from the separatrix is no longer Maxwellian and has gained energy. An effective resistivity at the X point is given, and the overall plasma motion is described.

*Work performed under the auspices of the USDOE.

NEOCLASSICAL RIPPLE TRANSPORT IN THE LOW COLLISIONALITY REGIME*

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The dominant contributions to neoclassical ripple transport coefficients arise from particles in the high energy tail of the distribution function -- $E \sim 6\ T_i$ for heat conductivity and $E \sim 4\ T_i$ for particle diffusion. Taking this effect into account, we find that the usual $1/\nu$ scaling is valid only for $\nu_{eff}(E) \gtrsim \omega_D(E)$ at $E \simeq 4\text{-}6\ T_i$, which is about two orders of magnitude $[(E/T_i)^{5/2}]$ larger than the conventional prediction, namely[1] $\nu_{eff}\ (T_i) \gtrsim \omega_D\ (T_i)$. The ion heat conductivity in the region where high energy particles can hit the wall is calculated by removing those particles from the energy integral in the usual ripple transport calculation. The result is found to compare favorably with a Monte Carlo calculation.[2] The diffusion coefficient in the region where particles can be collisionlessly detrapped before they drift to the wall is also estimated. The net effect of these clarifications of the $1/\nu$ scaling of neoclassical transport in nonaxisymmetric devices (tokamaks and stellarators) is to limit the effect to higher collisionality and thereby reduce the maximum possible transport coefficients.

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*Work supported by the U.S. DOE under contract DE-AC02-80ER53104.

SELF-CONSISTENCY AND SPACE-CHARGE EFFECTS IN INTENSE-BEAM FREE-ELECTRON LASERS*

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An analysis is presented of the influence of electron-beam density on the finite-interaction gain of a free-electron-laser amplifier operated in the stimulated-Thomson mode. The formulation is based on the Hamiltonian of a system comprised of two fields and a single particle, and it is shown how to incorporate density-dependent effects exactly into such a framework. When trapping and self-consistency (ie., the influence of changes in field amplitude on electron trajectories) are ignored, the finite-interaction gain displays a nonlinear dependence on beam density corresponding to Debye shielding transients; in this case, the gain formula agrees with that derived earlier[1] from the oscillation-center viewpoint.[2] For dense beams, the concurrent effect of self-consistency is studied numerically and its relative importance is assessed.

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*Work supported by the U. S. Department of Energy Contract #DE-A-S02-76-ET-53016 and the Office of Naval Research Contract N0014-79-C-0769.

Lagrangian Formulation of Neoclassical Transport Theory

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In the lowest collisionality (banana) regime, the dominant process is relaxation of the distribution f, to a function of constants of the motion. These actions then scatter under the influence of collisions to first relax f to a local Maxwellian, and then, slowly relax the radial action gradients to produce transport. The Lagrangian theory follows this hierarchy of relaxation processes, starting from a kinetic equation in terms of the actions alone

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \underline{J}} \cdot \frac{q}{2\pi} \underline{a} V_T f = C^J(f) = - \frac{\partial}{\partial \underline{J}} \cdot \underline{\Gamma}(f),$$

where C^J is a generalized collision operator and V_T is the toroidal inductive voltage. The theory does not require symmetry but assumes only the existence of three invariant actions J_1, J_2, J_3, with well ordered frequencies $\omega_1 >> \omega_2 >> \omega_3$. The energy is then principally a function of J_1, J_2, the "velocity" variables, while J_3 is the "radial" parameter. Transport equations are obtained directly by the reduced moments over J_1 and J_2. The transport coefficients are obtained by a straightforward expansion in the small parameter δ measuring the ratio of radial scattering to velocity scattering rates. The Lagrangian theory has the conceptual advantage of being a direct expression of the microscopic processes and allows the various fluxes to be interpreted in detail. The interpretations along with a comparison to conventional (Eulerian) theory are given.

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POSTER SESSION

Collisionless Tearing and Twisting Modes In the Presence of Trapped Particle Drifts

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The effects of the bounce averaged toroidal drifts of the trapped particles on the stability of the collisionless tearing and twisting mdoes is investigated. Since the current contributed by the trapped particles is proportional to the electrostatic potential ϕ alone, simple Ohm's law $J_{\parallel} = \sigma_{\parallel} E_{\parallel}$ is not valid. Perturbative techniques are developed to analytically obtain the new dispersion relation. Exact numerical solutions are also presented.

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POSTER SESSION

UCRL-85634

THREE-DIMENSIONAL ANALYSIS OF BALLOONING MODES IN TANDEM MIRRORS

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ABSTRACT

Finite ion gyro-radius effects eliminate highly localized (i.e., large mode number) ballooning modes. A quantitative analysis of this effect in non-axisymmetric tandem mirrors requires the solution of a 3-D eigenvalue problem. This problem is solved by extending WKB theory to many dimensions through the use of quasi-classical mechanics. The formalism of quasi-classical mechanics relates the solution of a partial differential equation to the Hamiltonian motion of a ray. This 3-D problem may be reduced to three 1-D problems by exploiting the disparate time scales of the ray trajectory.

The most rapid motion is along the equilibrium magnetic field. Hence, we first solve the ballooning mode equation along each magnetic field line. The solution at this level yields a local dispersion relation $D(\alpha,\beta,k_\alpha,k_\beta,\omega)$, where (α,β) label field lines, and (k_α,k_β) are the corresponding components of the wave vector. This dispersion relation is the Hamiltonian governing motion of the ray in the plane perpendicular to $\vec{B}$.

In quadrupole stabilized tandem mirrors flux surfaces have highly elliptical cross-sections. Because it is easier to bend flux bundles perpendicular to the flat plane, there is a rapid quiver in the ray trajectories in this plane. This quiver is the intermediate time scale; the associated action is a constant of the ray motion. This action and the effective Hamiltonian are the two constants of motion required to complete the solution of the ray motion. The dispersion relation is obtained by standard quantization techniques, first in the intermediate and finally in the slow motion. Results applicable to the TMX-U experiments at LLNL will be presented. We find that this self-consistent treatment of finite gyro-radius effects significantly increases the β limits.

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Renormalized Tearing Mode Turbulence and the Major Disruption

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An analytic theory of resistive fluid turbulence in tokamaks is developed and applied to the major disruption. The reduced MHD equations are renormalized using the Direct Interaction Approximation, thus guaranteeing energy conservation. Consistent renormalization of the $\underset{\sim}{V} \times \underset{\sim}{B}$ nonlinearity in Ohm's law yields an enhanced resistivity driven by turbulent convection ($<\tilde{V}^2>$), rather than by the magnetic fluctuations ($<\tilde{B}^2>$) emphasized in some previous studies. In the equation of motion, renormalization of the $\underset{\sim}{J} \times \underset{\sim}{B}$ nonlinearity results in a vorticity enhancing term, due to magnetic fluctuations,[1] while renormalization of the $(\underset{\sim}{V} \cdot \underset{\sim}{\nabla})\underset{\sim}{V}$ nonlinearity yields turbulent fluid viscosity and additional vorticity enhancement. In the final phase of the disruption, when a bath of fine-scale fluid turbulence has been generated, detailed considerations show that enhanced resistivity has the dominant effect.

For a low m ($q = 3/2$) tearing mode, solution of the renormalized equations during the turbulent phase yields a growth rate analogous to the classical case but increased by turbulent resistivity and slightly modified by vorticity enhancement. The analytical prediction is in excellent accord with computational results. The theory is extended to describe the quasilinear diffusion of the toroidal current and (from a renormalized two-point theory) the evolution of the magnetic energy, which is directly related to the negative voltage spike. Preliminary results indicate that qualitative features, magnitudes and time scales of these processes are consistent with the numerical results.

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THE AMBIPOLAR ELECTRIC FIELD IN STOCHASTIC B-FIELD MODELS*

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ABSTRACT

In a tokamak, electrons transitting stochastic magnetic field lines have a diffusion coefficient $\sim (v_{Te}/v_{Ti})$ greater than the ions. As a result, a positive radial electric field arises in the tokamak, limiting the electron flux to the ion flux. Using the guiding center drift equation in cylindrical coordinates, and including the radial electric field E_r, we find an operator similar to Ref. 1 for the effects of a given stochastic magnetic field on the flux surface averaged distribution function:

$$\frac{\partial f}{\partial t}(v_\perp, v_\parallel, r) = \frac{|v_\parallel|}{r} L\, r\, D_{st}\, Lf \quad , \tag{1}$$

where $L = \partial/\partial r - eE_r/mv_\parallel \cdot \partial/\partial v_\parallel$, r is the radial coordinate, $D_{st} = \pi\langle(\delta B_r/B)^2\rangle[L_A^{-1} + \lambda_{mfp}^{-1}(v_\parallel)]^{-1}$ is the diffusion coefficient of the magnetic field as seen by the particle,[2] and L_A is the autocorrelation length of the magnetic field. By assuming a local Maxwellian in the right-hand side of Eq. (1), we obtain new radial transport equations for particle density and energy. Particle flux is consistent with the Einstein relation. In the large mass ratio limit, and $T_i \lesssim T_e$, the equating of electron and ion fluxes gives

$$E_r = \frac{T_e}{e}\frac{\partial}{\partial r}\ln(nT_e^{1/2}) \quad . \tag{2}$$

Transport implications of the radial field are discussed.

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Near-Term Feasibility of Advanced Fuel Fusion Reactors*

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Near-term experiments on the ignition conditions[(1)] for advanced fuels (D-He^3 and D-D catalyzed) are shown to be feasible on the basis of existing technologies and of our present understanding of experiments on magnetically confined, toroidal plasmas. We consider in particular high-field and particle density experiments, capable of reaching $n\tau_E \gtrsim 5\times10^{14} sec/cm^3$, to the extent that the known form of the anomalous electron thermal conductivity can be extended to the regimes of interest, and attaining plasma currents of about 6 MA in order to confine the 14.5 MeV protons produced by the relevant fusion reactions. The considered heating cycles involve achieving D-T ignition first, by the combination of ohmic heating and r.f. heating at twice the tritium cyclotron frequency. Then He^3 is injected until peak ion temperatures of about 65 keV are reached and $\langle\beta\rangle \gtrsim 10\%$ is achieved while preserving the macroscopic stability of the plasma column according to the criteria, relevant to the finding of the "second stability region" indicated in Ref. 2.

In these conditions, cyclotron radiation emission is found to account for about 10% of all losses.[(3)] The effects of nuclear elastic scattering, fusion reaction propagation and self-interaction between reaction products and "promoted" (in energy) fuel ions have been considered.[(4)] A study on the technological[(3)] feasibility of these experiments has been carried out taking into account recent advances made in the structural analysis and in the technology of the relevant magnet systems.

*Sponsored in part by the United States Department of Energy.

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A MONTE CARLO FORMALISM FOR STUDYING THE BANANA-KINETIC EQUATION IN TOROIDAL SYSTEMS WITH FIELD RIPPLE*

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In the ripple-plateau regime of collisionality the banana-kinetic equation for radial transport in a rippled toroidal field can be solved analytically, using the random phase approximation, to give the so-called "Ripple-Plateau" transport coefficients for banana-drift diffusion.[1,2] In the ripple-collisionless regime $[\nu_{*i} < 1/(Nq)^2]$, in the presence of weak toroidal precession ($N\Delta\phi < 1$), analytic solutions are also possible.[3] Toroidal precession is large, however, for fusion products, supra-thermal ions, and even thermal reactor plasmas, especially in the hot ion mode. In the ripple-collisionless, precessional regime, Monte Carlo techniques can be applied to the banana-kinetic equation to study radial banana-drift transport. An area-preserving mapping has been developed to represent the collisionless effects of small toroidal field ripple (i.e., $\varepsilon|\sin(\theta_b)|/(Nq\delta) > 1$) on the confinement of energetic particles, where the toroidal magnetic field is modelled as $B = B_o R_o(1 + \delta(r,\theta)\sin N\phi)/R$ and θ_b is the poloidal angle of the banana tip. The radial variation of the banana length plays a crucial role in the onset of ergodicity in this mapping. The vanishing of the last KAM surface gives a simple criterion for loss of collisionless confinement of banana orbits due to ripple. Namely for confinement we obtain the restriction

$$\delta \lesssim \frac{\varepsilon^{3/2}|\sin\theta_b|^{1/2}}{\pi^{1/2}\, q^{3/2} \rho_L N^{3/2} \phi_b}, \tag{1}$$

with $\phi_b = 2q\theta_b$, which for typical INTOR parameters gives $\delta < 0.3\%$. For ripple values larger than this ergodic drifts occur, and the resulting quasi-linear diffusion coefficient is precisely the "Ripple-Plateau" value. Collisional transport under non-ergodic conditions and the transition to ergodicity are important because for energetic fusion products "Ripple-Plateau" diffusion results in rapid loss of all banana-trapped particles. A Monte Carlo analogue of the bounce-integrated Fokker-Planck operator[4] appropriate for use in the banana-kinetic equation, is also presented. Taken together the mapping and collision operator constitute a complete Monte Carlo formalism for studying the banana-kinetic equation in toroidal systems. Initial results using this formalism will be presented.

*Work supported by U. S. DoE Contract #DE-AC02-76-CHO3073.

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THEORETICAL VIEW OF A HIGH β TOROIDAL PLASMA EXPERIMENT*

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We describe theoretical efforts to explain the departure from ideal MHD theory of detailed experimental observations of the stability and equilibrium of a high β toroidal plasma. In the Wisconsin Levitated Toroidal Octupole a range of stable plasmas have been created with β values from 8% to 35%, 2 to 9 times the MHD ballooning instability β limit of 4%. β decays in 1000-6000 Alfven times with no β-related fluctuations in magnetic field, density or electrostatic potential. From β = 8% to 35% the plasma varies from nearly ideal fluidlike (collisional, highly conducting, small but finite gyroradii) to clearly kinetic (large gyroradii and viscous).

The ideal MHD, radially local, infinite toroidal mode number, m, prediction employs self-consistent equilibria with the experimental pressure profile. Inclusion of non-infinite m produces a stabilizing effect insufficient to explain the experiment, but allows exact calculation of the radial mode structure.

A kinetic calculation, in the zero gyroradius limit, predicts that the manifestation of the ballooning mode as an oscillatory ion drift wave roughly doubles the β limit. Particle free streaming is also weakly stabilizing.

Measured experimental profiles of the equilibrium diamagnetism indicates good agreement with MHD in the fluidlike (β=8%) case but a seven-fold discrepency at β = 35%. Preliminary calculation indicates that ion gyroviscosity is responsible. The effect of the reduced diamagnetic current on stability is large since the marginal stability calculation reveals that the critical stability parameter is diamagnetic current and not β.

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

RELAXATION TOWARD STATES OF MINIMUM ENERGY IN A COMPACT TORUS*

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A finite-difference, resistive, compressible magnetohydrodynamic code is used to follow the long-time evolution of decaying non-equilibrium states inside a rigid, perfectly-conducting, finite cylinder. The system evolves toward a force-free equilibrium of spheromak type, which minimizes the energy-to-magnetic helicity ratio in accord with a conjecture of Taylor. For the parameters chosen, the magnetic Reynolds number is considerably higher than the mechanical Reynolds number. The energy, which is mostly magnetic, tends to decay in bursts associated with current filamentation and magnetic reconnection. The field variables have all three components in the geometry considered, but all variables are independent of the azimuthal coordinate. For this case, there is another non-dissipative invariant, a flux invariant, which roughly parallels the mean-square vector potential in earlier "selective decay" MHD calculations. Under at least some circumstances, this flux invariant decays even less than magnetic helicity, so that while the energy-to-helicity ratio is decaying, so also is the helicity-to-flux invariant ratio decaying. This throws the theory into some disarray, but at least opens the possibility of selective decay to states which are not force-free and have finite pressure gradients.

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Tilt and Shift Mode Stability in Spheromaks with Line Tying*

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Numerial studies of MHD stability of force free spheromak plasmas to $n = 1$ free boundary tilt and radial shift modes are presented. The exterior region of open field lines is treated either as a vacuum or as a perfectly conducting plasma. In the latter case the effect of line tying of the open field lines to the cylindrical conductor is present; this is found to improve stability greatly. For example, without line tying neither the radial nor the axial wall may be removed to large distances without the other wall being extremely close. With line tying, it appears that the axial wall may be removed to a large distance with the radial wall at a finite distance from the separatrix.

Various current profile models [$j = \mu(\psi)\underset{\sim}{B}$] have been studied. It is found that smoothing of the current profile near the separatrix or the introduction of a flux hole are both stabilizing. Equilibria which have optimal stability properties to the tilt and shift modes are oblate, with length to diameter ratio about 0.6, nearly independent of current profile, boundary conditions on the equilibrium, or whether line tying exists on the open field lines.

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LOWER HYBRID WAVE RAY TRACING FOR SPHEROMAK HEATING

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ABSTRACT

Auxiliary heating of spheromaks may be essential to bring such plasmas to ignition. Here, we assess the effectiveness of lower hybrid wave heating in spheromaks. As a model for plasma equilibrium we use a force free field configuration.[1] Since there is only one degree of symmetry in spheromak geometry we use ray tracing to follow the wave energy. The dispersion relation is fully electromagnetic and was derived using the two fluid model assuming $\omega \gg k_{\parallel} V_e$, kV_i, and $k\rho_i \gg 1$, $k\rho_e \ll 1$. Results up to date show that electrons are preferentially heated over ions, even in the regime $\omega \simeq \omega_{LH}$, where ω_{LH} is the maximum value of the lower hybrid frequency in the plasma. The location of the region of energy deposition turns out to be very sensitive to initial values of wave parameters as well as to the location of the launching structure.

(a) Auburn U. and SAI
(b) NRL
(c) Maryland U.
(d) M.I.T.

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Beta Critical in the Second Region of Stability*

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The second region of stability to ballooning modes in high beta tokamaks is investigated for low toroidal mode numbers. A parameter study has been done to determine beta critical as a function of shear, safety factor on axis, peakedness of the pressure profile, and aspect ratio. The results of the study indicate that in general finite aspect ratio is destabilizing, while a flat pressure profile, high shear and high q on axis are stabilizing. These trends are consistent with a simple model for ballooning modes. These results are compared with the predictions of W.K.B. theory for the 1/n correction to the n = ∞ ballooning mode theory. Agreement of these results with the large aspect ratio HIB code is also presented.[1]

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POSTER SESSION

Field Error Studies in Modular Stellarators*

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Small magnetic field errors can have a disastrous effect on the magnetic surfaces, and hence confinement, in toroidal systems. Gourdon et. al.[1] have investigated the structure of magnetic surfaces in an $\ell = 3$ stellarator and torsatron, and Rehker and Wobig[2] for the WVII-a $\ell = 2$ classical stellarator. The University of Wisconsin is currently constructing IMS (the Interchangeable Module Stellarator) which is a modular stellarator device. To insure well formed magnetic surfaces with no large island structure, an investigation into the effects of coil construction and alignment errors in modular stellarators was initiated.

Three types of errors were examined: 1) random errors in the conductor path of the coil-this sets the fabrication tolerances, 2) random errors in the placement of the individual coils in the machine-this sets the alignment tolerances when putting the machine together, and 3) systematic errors repeated from coil to coil-this effects current feed design.

Results will be presented on construction and alignment tolerances for modular stellarators as well as design constraints arising from periodic feed errors.

* Work supported by U.S. D.O.E. under Contract No. DE-AS02-78ET53082 and NSF under Grant ECS-79-25418.

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SCALAR AND TENSOR PRESSURE DISTRIBUTION FOR AXISYMMETRIC MHD ANALYSIS OF BARRIER TANDEM MIRRORS*

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The ideal MHD ballooning β limit of a series of axisymmetric magnetic configurations with stabilized thermal barriers has been investigated. More realistic scalar and tensor pressure profiles are prescribed and implemented in a modified version of the LLNL[(1)] code to optimize the configurations. The electrostatic potential profiles $\phi(s)$ consistent with the pressure profiles are also determined by solving Poisson's equation. The highest plasma pressures for which the given magnetic field line is MHD-stable for different configurations are calculated. Current results are a factor of ~ 3 lower than the previously reported results.[(2)]

*Work supported by USDOE.

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POSTER SESSION DESIRED

1981 SHERWOOD MEETING
ANNUAL CONTROLLED FUSION THEORY CONFERENCE
APRIL 8 – 10, 1981
THE UNIVERSITY OF TEXAS
AUSTIN, TEXAS

Analysis of Heating and Thermal Stability Near Ignition

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ABSTRACT

We present 0- and 1-dimensional analyses, and computer simulations, of tokamak heating to achieve thermally stable high-Q operation just below ignition. Ion transport is assumed to be neoclassical and electron transport is taken to be anomalous (as in PLT and Alcator). From 0-dimensional power balance considerations ($d(nT)/dt = P_\alpha + P_h - P_{rad} - P_{diff} \equiv F(n,T)$) we show that in the temperature range $T < T_{id}$ (where total radiation losses, P_{rad}, dominate the thermonuclear yield, P_α) the plasma heats only if simultaneously the heating power P_h exceeds the diffusion losses P_{diff} and the density lies below the equilibrium curve $F(n,T) = 0$. Above T_{id}, $P_h > P_{diff}$ is no longer necessary for heating; at any desired operating density, the plasma can attain a thermally stable, high Q equilibrium using a temperature controlled reduction of P_h [1].

This 0-dimensional analysis of heating and control stratagem is shown to be valid also with 1-dimensional radial variations taken into account. First, we extend a previously developed 1-dimensional thermal stability criterion [2] to encompass the $P_h(T)$ term, verifying the principal features of the 0-dimensional stability condition. Second, complete heating plus control simulations are performed using a 1-dimensional transport code with a P_h controlled as a function of the peak T_i. It proves advantageous to concentrate P_h in the plasma core since the per volume diffusion losses are greatest there. The simulation results that we obtain are compared with core-model 0-dimensional analysis.

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LONG WAVELENGTH COLLISIONAL TEARING MODES IN A STOCHASTIC MAGNETIC FIELD*

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Statistical equations which characterize long wavelength resistive tearing modes when the magnetic field is stochastic are derived. The stochastically nonlinear $\underline{V} \times \underline{B}$ convection and $\underline{J} \times \underline{B}$ force in the equations of resistive magnetohydrodynamics are analyzed using techniques of functional renormalization. Consistent with the short wavelength nature of the turbulence, a statistical closure approximation based on near Gaussian statistics is used to obtain the nonlinear dispersion relation. The theory predicts a broadening of the current layer due to enhanced perpendicular electron motion. This broadening is significant for fluctuation levels as small as $\langle(\delta B/B)^2\rangle \sim 10^{-8}$. As a consequence, the regime of algebraic growth[1] is attained only when the magnetic energy density of the mode exceeds the total magnetic energy density of all the other fluctuations. An extension of the theory which includes the effect of the parallel electron pressure gradient in Ohm's law is discussed. A form of Ohm's law containing a turbulent electron "viscosity" is obtained. This form leads to a growth rate which is significantly larger than that obtained for the same fluctuation level from a similar, but not identical, form hypothesized by Kaw, Valeo, and Rutherford.[2]

*Research supported by the Department of Energy.

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Energy Multiplication in Tokamaks with Enhanced Radial Electric Fields*

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Externally-imposed radial electric fields in a tokamak take advantage of the differences in cross-field conductivity between fuel and impurity ions to increase the fusion power output. An inward-directed 10 kV/m electric field improves fuel confinement without significantly increasing contamination by fusion-product alpha particles.[1] The radial electric field which will be present in a fusing tokamak plasma due to prompt alpha losses to the first wall has been calculated.[2] Stagnation-orbit injection of unbalanced charge into the plasma has been suggested for magnitude and shape modification[3].

A self-consistent calculation of the generation of a radial electric field and of the subsequent time evolution of the plasma is presented here. The imposed electric field is limited to ~10 kV/m to hold the $\vec{E} \times \vec{B}$ rotation below acoustic velocities. The simplified plasma model used minimizes secondary effects of the radial electric field. The present study considers a TFTR-sized fusing plasma with long burn time. Injection of negative fuel-ions and of electrons is modelled for peak injection density at $r/a = 0.45$ to 0.85. The plasma energy multiplication factor, Q-value, is taken as the figure of merit for plasma performance.

Electron generation of the electric field requires higher injection energies and does not refuel the plasma as negative fuel-ion generation does. Much lower Q-values therefore characterize this injection. Negative-fuel injection, however, raises the Q-value from about 0.35 (without injection) to ignition. At short times ($\lesssim$ 10-30 sec.) maintenance of the plasma temperature at the centerline requires more energy than injection to $r/a = 0.45$, making deep injection optimal. At longer times the energy losses from the plasma decrease and less energetic edge injection becomes preferable.

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ABSTRACT

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LINEAR THETA PINCH REACTOR WITH PULSED MIRROR END PLUG

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It is shown that by suitably pulsing a magnetic mirror end plug of a linear theta pinch, one can produce an additional axial plugging force. This force in the half-mirror region closer to the theta pinch end, is found to be substantial. The pulsing time constant is chosen in relation to the anomalous magnetic field diffusion time in the presence of lower hybrid drift instability, so as to optimize the plugging action. The end loss calculated via a steady isentropic, ideal hydromagnetic parallel flow model, is found to be substantially reduced. A system consisting of a linear theta pinch with sequentially pulsed multi-mirror end plugs is proposed, which shows promise of fusion feasibility. A 100 m long linear theta pinch with 50 m long end plug sections at each end, yields $n\tau_{conf} \sim 2 \times 10^{15}$ cm^{-3} sec. The corresponding net electrical power output from a reactor will be .5 GW.

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APS Member 3/15/81

POSTER SESSION

ENERGY PRINCIPLE CODE FOR MHD TEARING MODES IN A GENERAL CROSS SECTION PLASMA*

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ABSTRACT

The stability of magnetohydrodynamic (MHD) tearing modes in a general cross section tokamak plasma is studied by using a finite hybrid element method in a nonuniform intrinsic flux coordinate system. The problem is formulated in terms of an energy principle for the driving potential energy outside tearing layers with all the possible modes included. The application to a circular cross section tokamak with a large aspect ratio produces results in good agreement with those previously known. This agreement includes the quantitative values of the usual stability parameter Δ' and the eigenfunction itself which is checked through the calculation of saturated island widths. The typical results for intrinsic noncircular equilibria will also be presented.

*Work supported by the Department of Energy, Contract DE-AT03-76ET51011.

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1981 Sherwood Meeting

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Analytical Modeling of Sawtooth Oscillations in Tokamaks*

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Abstract

Sawtooth relaxation oscillations are analysed using Kadomtsev's disruption model.[1] The magnetic flux and the total energy including magnetic energy within the disruptive region are conserved during the disruptive phase of the oscillation. During the relaxation phase, the magnetic diffusion equation and the energy balance equation including thermal conduction loss, radiation loss and beam heating effects are linearized. Analytical solutions for the sawtooth period are then obtained in terms of the skin time, ohmic heating time, beam heating time, energy confinement time and radiation cooling time. This analytical model is compared with various experimental results from PDX.

*This work support by the United States Department of Energy Contract No. DE-AC02-76-CHO-3073.

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RF Plugging Near the Ion Cyclotron Frequency*

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A sizeable literature exists on the usage of the large ponderomotive force which is expected to be produced by an RF signal near the ion cyclotron frequency (i.e., $\omega \simeq \Omega_i$). Outstanding among the applications are the RF plugging of open-ended systems and schemes for isotope separation. The central concept in this area is the time averaged ponderomotive potential, which when calculated for a cold plasma and in the time asymptotic limit yields a singularity as ω approaches Ω_i. In reality, this singularity cannot exist because as $\omega \rightarrow \Omega_i$ ion cyclotron resonance heating occurs and the concept of a potential disappears, i.e., the perpendicular energy increases secularly in time. The present analytic, numerical, and experimental study aims at illustrating the correct behavior of the ponderomotive effect and its maximum stopping power when ion cyclotron resonance heating is retained. It is found that the peak stopping power for a single ion occurs at a frequency difference $\Delta\omega = \pi\tau^{-1}$, where τ is the transit time through the field structure. The geometry considered is an idealized electrostatic coupler which can be well approximated in the laboratory and simplifies the analysis. The calculations are based on the Born approximation and show excellent agreement with numerical orbit studies and with experimental results using collimated test ions in a uniform magnetic field. The experiments have also been extended to produce RF plugging of a magnetized pure ion plasma. The plugging effect has been demonstrated, but its efficiency is limited by cyclotron resonance heating, as expected from the analysis. Results of the scaling of RF plugging with various parameters are to be presented.

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MHD Stable Equilibria of an Ion Ring Confined Plasma†

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We study the ideal MHD stability of perturbations in a plasma confined by an axisymmetric field reversed ion ring in the absence of a toroidal field. The ASSYST code solves the Grad-Shafranov equation with specified beam and pressure profiles and computes eigenvalues and eigenfunctions of the Euler-Lagrange equation derived from minimizing the energy integral on each flux surface. Modeling the beam as an exponential rigid rotor, we obtain MHD stable equilibria with $p_s/p_o \approx .036$ and $E_p/E_b \approx .12$, where p_s/p_o is the ratio of pressure on the separatrix to pressure at the O-point and E_p/E_b is the ratio of plasma energy to beam energy. We also study the stability of equilibria generated by RINGA[1] particle simulations.

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

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3B14

POSTER SESSION

STABILITY STUDY OF THE EXPANDED SPHEROMAK*

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ABSTRACT

Previous stability studies have shown that spheromaks are unstable without an external conducting wall. We investigate here the stability of the expanded spheromak, a configuration which includes an open field line plasma outside the closed field line spheromak plasma. The open field line plasma may provide some stabilization. The δW code, GATO,[1] which can handle the internal separatrix of a doublet configuration, is well suited for this study, and has shown good agreement with analytical results for spheromak.[2] We present the code modifications necessary to treat the expanded spheromak configuration. In order to test the code, a general class of analytic equilibrium has been derived for which the percentage of flux inside the separatrix can be easily varied to test the spheromak limit. Numerical spheromak equilibria are generated with a modified version of the equilibrium code, GAEQ.[3]

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*Work supported by the Department of Energy, Contract DE-AT03-76ET51011.

UNSTABLE ENTROPY MODE IN A CURRENT CARRYING TURBULENT PLASMA AND DOUBLE LAYER FORMATION*

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In the presence of a strong axial current, a non-isothermal plasma sets in ion acoustic turbulence giving rise to enhanced anomalous resistivity and inhibited thermal conductivity. This state is, however, shown to be unstable to a purely growing axial perturbation when $v_o^2 \nu / v_e^2 > k^2 x$; v_o, v_e, ν and x are the electron drift velocity, thermal velocity, collision frequency and thermal conductivity. A temperature perturbation enhances the local resistivity of electrons and raises their heating rate, further enhancing the temperature perturbation. When this tendency overpowers the opposing effect of thermal conduction, the instability grows. The nonlinear state of this instability has been analyzed and its relevance to the experimental results of Hollenstein, Gayol and Weibel[1] on the formation of double layers in a long plasma column has been discussed.

*Work supported by the Department of Energy and the Office of Naval Research.

[1] Ch. Hollenstein, M. Gayol and E. S. Weibel, PRL 45, 2110 (1980).

HAMILTONIAN FORMULATION OF THE GYROKINETIC EQUATION

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The guiding center Hamiltonian of a charged particle in arbitrary time independent magnetic fields is derived to first order in a Larmor radius expansion by canonical transformations. The time evolution of the particle distribution function is then determined by Liouville's equation. For low frequency perturbations, this equation can be immediately averaged over the gyrophase angle to obtain the linearized gyrokinetic equation derived first by Antonsen and Lane (1980)[1] and then later by Catto, Tang, and Baldwin (1981).[2] This alternative derivation is extended to determine the nonlinear contributions to the gyrokinetic equation.

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Alfvén Wave Heating of Toroidal Plasmas

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A promising scheme for providing supplementary heating to a magnetically confined plasma involves resonant excitation of the singular shear Alfvén wave. This is a mode which lies in the continuous spectrum of the linearized equations of ideal magnetohydrodynamics (MHD). The Tokapole II group at the University of Wisconsin in Madison is currently exploring the possibility of direct coupling to, and subsequent heating by, this wave in an axisymmetric tokamak, as are groups at the Ecole Polytechnique in Lausanne and at the University of Texas. In order to understand the significance of the experimental results, it is crucial that the theory be advanced to include the effects of toroidicity and noncircularity of the plasma cross section. These potentially important effects have often been neglected in the past. In this study, the equations which determine the ideal MHD continuous spectra in an axisymmetric tokamak equilibrium are analyzed using an expansion scheme in powers of the inverse aspect ratio. Resulting formulae have been evaluated for the parameters of the Tokapole II experiment. Mode coupling, induced by toroidicity or noncircularity, is shown to produce gaps in the spectra on or near rational surfaces for particular poloidal and toroidal mode numbers. These gaps are analogous to those which appear in the energy spectrum of a single electron in a periodic potential lattice. Through the use of Floquet theory, the same behavior of the spectra is shown to occur in takamaks for which the perturbation expansion is invalid. Generalized Floquet functions are introduced to extend these concepts to account for Alfvén wave excitation in totally asymmetric equilibria such as stellarators. Unless certain conditions are satisfied, it is unclear whether the MHD continuous spectrum exists in the absence of spatial symmetry.

1981 SHERWOOD THEORY MEETING

Austin, Texas - April 8-10, 1981

INTERNAL MODES AND TERMINATION OF QUIESCENCE FOR THE REVERSED FIELD PINCH*

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Termination of the quiescent period has been the principal limitation of heating in the ZT-40 Reversed-Field Pinch (RFP) experiment. The cause of this termination at present is poorly understood. In this paper we consider a model for termination of quiescence due to internal current-driven resistively-modified ideal MHD instabilities. These modes are directly anologous to the tokamak kink modes that violate the constant-ψ approximation and are driven by excess on-axis toroidal current density and insufficient shear.

Nonlinear simulations show that these modes exhibit global reconnection. Implications of this process to nonlinear mode coupling and termination of quiescence are discussed. Transport calculations and relevant linear and nonlinear resistive MHD calculations are presented.

*Work performed under the auspices of the USDOE.

POSTER SESSION REQUESTED

Monte Carlo Modeling of He Enrichment and Plenum Neutral Conditions in Divertor Devices*

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ABSTRACT

The Monte Carlo code DEGAS [1] for computing neutral transport in divertor devices with constant plasma conditions has been improved to include more realistic plasma profiles as well as neutral-neutral collisions in plenum chambers. Results from a survey over a range of plasma conditions for an INTOR-type divertor examining the question of He enrichment and using the improved code will be given. Refinements in the pseudo-collisional algorithm of DEGAS will also be presented.

*Work Supported by the U.S. DoE Contract No. DE-AC02-76-CHO3073.

[1] D. Heifetz et al., Poster 9S16, 1980 APS Meeting, Division of Plasma Physics.

Low Frequency Heating of Doublet*

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ABSTRACT

We continue to investigate low frequency (1000 Hz, possibly 60 Hz) heating of a doublet by oscillatory motion of the separatrix which induces a very sharp current peak localized near the moving separatrix. An improved alternating dimension non-linear initial value simulation code which imitates the actual F coils in a doublet is described. Impedences and associated eigenvalues and eigenvectors for oscillating F-coils are computed and compared to experimental results on Doublet-III, and to results from a linearized eigenfunction code.[1]

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*Work supported by U.S. DOE Contract No. DE-AC02-76ERO 3077

1. T.H. Jensen and W.B. Thompson, J. Plasma Phys. 19, 227, (1978)

UCRL-85635

A THEORY OF HOT ELECTRON PLASMAS

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ABSTRACT

Populations of energetic, highly anisotropic electrons have been created in many experiments (e.g., EBT, STM, and INTERM) by applying ECRH at the second harmonic. We find that many important features of these experiments, such as (i) the large anisotropy, (ii) the observation that the mean energy, $\overline{E}$, is independent of the microwave power, and (iii) the scaling of $\overline{E}$ with the magnetic scale length can be explained by a simple model in which the hot electron distribution function is determined mainly by the interaction with the heating field. The conditions that the microwave heating dominate the collisional drag sets a lower limit on the energy of the hot electron population,

$$E_{min}(\mathrm{keV}) \cong 300 \left[B(\mathrm{Tesla})\ n_e(10^{11}/\mathrm{cm}^3)\right]^{2/3} \Big/ \left[\varepsilon(\mathrm{V/cm})\right]^{4/3} .$$

Electrons with energies greater than E_{min} are spun up by the microwave heating field until they are lost by non-adiabatic scattering due to the magnetic field inhomogeniety at an energy

$$E_{max}(\mathrm{keV}) \sim 100 \left[B(\mathrm{Tesla})\ L_B(\mathrm{cm})\right]^2 ,$$

where L_B is the axial magnetic scale length. The model predicts an anisotropic distribution of hot electrons with $\overline{E} \cong 1/14\ E_{max}$. Analytic work, including a discussion of stochastic energy limits for second-harmonic heating, and the results of a bounce averaged Fokker-Planck code will be presented.

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POSTER PAPER

KINETIC BALLOONING-INTERCHANGE MODES IN TANDEM MIRRORS*

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A hybrid fluid-gyrokinetic derivation of the kinetic modifications to the ballooning-interchange eigenmode equation is presented which generalizes previous results.[1] By considering the long-thin ordering appropriate to mirror devices and employing an eikonal ansatz, the governing second-order differential equation (along a field line) is derived without assuming that the wave frequency ω is either large or small compared to the bounce and transit frequencies. Consequently, the restrictions employed in Ref. 1 are shown to be unnecessary. The derivation technique permits arbitrary asymmetry, beta, and pressure anisotropy, and the validity of the small parallel electric field assumption is affirmed. The techniques employed may also be appropriate in other devices.

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*Work supported by the U. S. Department of Energy under contract DE-AC03-79-ET-53057.

[1] W. M. Tang and P. J. Catto, Science Applications, Inc., Report No. SAI-254-80-594-LJ, PRI-15.

A Generalized Model of Field-Reversed Equilibria Created by Monoenergetic Ions.*

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A theoretical model of Reversed Field Ion Layer (RFIL) equilibria generalized to include warm electron currents, averaged magnetic multipole wells and nonideal ion current distributions is presented. Expanding on previous work by Post[1] and Brandenburg and Post[2] an ideal model of RFIL equilibria using monoenergetic ions is modified to include currents from other sources and nonuniform background fields. As in the ideal model rotational symmetry and infinite length in the z direction are assumed. The generalized model is used to study the effect of Boltzmann electrons, an additional group of ions at different angular momentum from the main ion group, and a quadratic magnetic well (treated in an azimuthally-averaged sense) on an RFIL. The RFIL studied was found to compensate for the effect of these deviations from ideality, giving field profiles that deviated only slightly from the ideal case. A variational formulation of the ideal and generalized RFL equilibria is presented and the results of the generalized RFIL study are discussed in terms of energy minima.

1 Post, R. F., APS Bull. 22, 1192 (1977).
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Requested: Poster

COUPLING OF HOT ELECTRON INTERCHANGE AND ION BERNSTEIN MODES IN EBT*

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ABSTRACT

Previous stability studies of hot electron ring and background plasma in EBT have been pursued in low frequency ($\omega \ll \Omega_{ci}$) and intermediate frequency ($\omega \sim \Omega_{ci}$) with small Larmor radius approximation ($k_\perp \rho_i \ll 1$).

Present experimental parameters indicate the importance of finite Larmor radius effects and therefore the importance of higher cyclotron harmonics. We derive and analyze the dispersion relation which includes both effects. Our result reduces to those of Nelson[1] and Van Dam and Lee[2] in the appropriate limit. Coupling of the hot electron interchange mode to compressional Alfvén wave as pointed out by El Nadi[3] is also recovered. However, when finite Larmor radius is included, further coupling of the compressional Alfvén wave to the cyclotron harmonics is observed to excite a new ion Bernstein instability. This leads to instability channels in the stability diagram. The stability boundary of Nelson, Van Dam, and Lee is connected to the stability boundary due to the ion-cyclotron mode at large hot electron beta.

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

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POSTER SESSION REQUESTED.

1981 SHERWOOD THEORY MEETING
Austin Texas - April 8-10, 1981

SPACE-RESOLVED CYCLOTRON RADIATION AS A POTENTIAL FIELD PROFILE DIAGNOSTIC*

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We analyze the use of cyclotron radiation as a diagnostic tool to infer the radial profile, time resolved if feasible, of magnetic field distributions in Reversed-Field Pinch (RFP) configurations. Success would imply a useful advance toward obtaining noninvasive experimental measurements of power balance and energy containment time in dense toroidal pinches displaying strong radial gradients of toroidal field.

We derive exact expressions for the cyclotron harmonic power output, per unit solid angle, contributed by a chordal volume (truncated cone) of given mean cross-sectional area located at a distance h from the magnetic axis. This power is the total from a given cyclotron harmonic, i.e., is integrated over the narrow linewidth of the harmonic, for which the radiation is not trapped or absorbed. By "exact" is meant that the underlaying expressions for the radiation from a given electron have the correct relativistic angular distribution with respect to the local field direction, and that the electron distribution function is a relativistically exact thermal one. Numerical and approximate analytical evaluations of the chord output were used to check the correctness of these expressions.

The aim is to use collimated radiation detectors, operating in the millimeter microwave range, to define and resolve the output from each of a set of such chords of varying h, and to invert the resulting h-profile of the radiation into radial profiles of the toroidal and poloidal field components. A numerical technique[1], forward optimization, is available to perform this complicated inversion, yielding suitably parametrized functions of minor radius for the field components.

We examine a number of experimental, technical, and computational difficulties that presently bar the realization of this diagnostic program, and assess the prospects for its successful application.

Reference

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*This work was performed under the auspices of the USDOE.

UCRL-85631

SENSITIVITY OF EQUILIBRIUM TO COIL CONFIGURATION IN TANDEM MIRRORS

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ABSTRACT

The tandem equilibrium and balloon code TEBACO has been used to study the dependence of finite-β equilibrium[1] on the structure of the vacuum magnetic field in tandem mirrors. The most important factor determining the robustness of equilibrium, that is, its resistance to deformation with increasing β, is the parallel current. The geodesic curvature controls the parallel current, and thereby the extent to which flux surfaces are deformed relative to their vacuum shapes. By forcing the pressure-weighted "$d\ell/B$" integral of the geodesic curvature to be small, the parallel current can be correspondingly reduced and the equilibrium rendered more robust. Since the drift of particle guiding centers off a flux surface is also determined by the geodesic curvature, a collateral effect is an improvement in guiding-center drift orbits. Applications to the design of MFTF-B are presented.

1. L. D. Pearlstein, T. B. Kaiser and W. A. Newcomb, Lawrence Livermore National Laboratory Report UCRL-85039 (1980).

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POSTER SESSION

STOCHASTIC HEATING OF IONS BY AN ION-CYCLOTRON WAVE IN AN INHOMOGENEOUS MAGNETIC FIELD*

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Ion heating by waves in the ion cyclotron frequency range is studied for a plasma in a strongly inhomogeneous magnetic field, of the type found in multipole or surmac configurations. We concentrate on the effect of strong magnetic field inhomogeneity in the direction perpendicular to the field line, the scale length of the inhomogeneity being of the same order as the ion-cyclotron radius. In such a strongly inhomogeneous magnetic field, collisionless ion trajectories are periodic but anharmonic (i.e., non-sinusoidal). In the presence of an external electromagnetic wave, whose wavelength is large compared to the scale length of the static field inhomogeneity, the ion motion can be described as a one-dimensional forced anharmonic oscillation. Resonances of the external wave with the natural oscillations of the ions lead to islands in phase space and a classical transition from superadiabatic to stochastic behavior. We find that ions with perpendicular energy above some critical value (which depends on the wave amplitude) are stochastically accelerated, a result which should lead to generation of a hot ion component in ICRF heating of multipoles.

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UCRL-85637

ION THERMAL CONDUCTION IN COMPACT TOROIDS

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ABSTRACT

Classical cross-field ion thermal conduction is very large in present compact torus experiments, and may dominate their power balance. A point transport model is presented, based on analytic evaluation of classical transport coefficients in realistic geometry. The model assumes that energy flows from the magnetic field to the electrons by ohmic heating, from electrons to ions by equilibration, and from ions to the wall by cross-field transport. On a short time scale the plasma reaches a quasi-steady state, in which ion thermal conduction balances ohmic heating. For moderate or high density ($n \gtrsim n_{cr} \doteq 5 \times 10^{16}/R^2$, R = separatrix radius, in cm.) this steady state is characterized by a universal beta, $\beta_e \approx \beta_i \approx 4\%$, where β measures average pressure relative to the peak field, $\hat{B}$. Thus, for $n \gtrsim n_{cr}$, $T_e \approx T_i \sim 1/n$. For the LLNL Beta-II experiment, this gives $T_e \approx T_i \approx 10$ eV, in rough agreement with experiment. For densities below n_c, $T_i \sim n^2$. Thus there is a optimal density n_{cr}, which maximizes ion temperature: $T_{max}(eV) \sim \hat{B}^2 R^2/100$. Present experiments have $n >> n_{cr}$. On a longer time scale, discharge current is shown to decay to zero in a finite time: $I(t) = I(o)(1 - t/t_f)^{1/3}$.

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POSTER SESSION

MINIMUM NUMBER OF MODES FOR THE APPROXIMATION OF THE SOLUTIONS OF THE NAVIER-STOKES EQUATION*

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As proved by Foias and Prodi [1], the long time behavior of the 2-D solutions of the Navier-Stokes equation depends only upon a finite number of Fourier modes. Foias and I have now demonstrated [2] that the 3-D solutions also possess this property, which has important consequences for numerical simulations, namely: 1) failure to use enough modes may lead to completely erroneous results; 2) the number of modes needed for 3-D flow calculations is proportional to the third power of the number needed for 2-D flows; 3) a test can in principle be devised for checking the reliability of numerically determined Galerkin approximations [3]. The connection between the above property and conventional turbulence theory will be indicated [4].

Using an MHD extension of the Bénard problem as an example it is shown how to construct Galerkin approximations which conserve energy exactly [5].

Implications of the above results for MFE calculations will be discussed.

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UCRL-85632

PARAMETER SURVEY OF MFTF-B

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ABSTRACT

The zero-D transport code, TANDEM, was used to survey the operating range of the large tandem mirror, MFTF-B. The nominal MFTF-B plasma parameters include center cell values of $n_c = 2.1 \times 10^{13}$ cm^{-3}, $T_{ic} = 15$ keV, $T_{ec} = 9$ keV, $\phi_e = 50$ kV and $\phi_c = 28$ kV. The yin-yang parameters are $T_{ip} = 56$ keV, $n_{pe} = 5.5 \times 10^{13}$ and $\phi_p = 59$ kV. At the peak potential point in the A cell, $n = 7 \times 10^{12}$, $T_e = 30$ keV and $\phi_a = 78$ kV. By varying the neutral beam current, rf power and gas feed to various regions of the tandem mirror, the range of values for plasma density and temperature and the plasma potential in the center cell, yin-yang, barrier and A-cell regions were determined.

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UCRL-85630

ELECTRON THERMAL AND WARM PLASMA EFFECTS ON ION-CYCLOTRON MICROINSTABILITIES IN MIRROR DEVICES

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ABSTRACT

In mirror devices, electrons are trapped in the electrostatic potential well associated with the peaked axial profile of the hot neutral beam injected ions. For the 2XIIB and TMX mirror devices at Livermore, the axial bounce frequency ω_b, of the trapped electrons can be close to the frequency of spontaneous RF fluctuations at $\omega = \omega_c$, where ω_c is the ion-cyclotron frequency. Because we wish to consider the details of the electron response, the hot ions are assumed to have a simple adiabatic response which gives the ion diamagnetic drift mode for an infinite plasma. Even though the primary role of the axial electron motion on the RF is to partially short out the parallel electric field, we find significant Landau damping can occur when the azimuthal wavenumber k_y is not too small for $\omega \approx n\omega_b$, where n is an integer. The damping occurs because the spatial variation of the magnetic field gives a velocity-dependent spread in the bounce frequency. The electron response is written in terms of an integral equation which, together with the adiabatic ion response, is solved numerically for the axial eignefunctions.

To model the wave propagation toward the solenoid in TMX, we add a component of warm plasma extending beyond the hot plasma region and solve for the eigenfunctions again. Significant electron Landau damping can also occur in this region. With hot plasma alone, only a mode propagating in the ion diamagnetic direction with $k_y \sim \omega/v_{dia}$ is found. In contrast, the presence of the warm plasma allows existence of both $\pm k_y$ modes with this range of k_y.

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POSTER SESSION

Analysis of the Density Profiles in Various Experiments*

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We have analyzed the steady state density profiles in a variety of discharges obtained on the FT device[1] in order to determine the parameters which have a strong influence on these profiles. We found that there is no clear correlation between $n_o/\bar{n}_e$ and the line-average density $\bar{n}_e$, but this ratio tends to increase when the plasma current decreases.

Comparison of these results with the behavior of the density profiles in Alcator A[2] and TFR[3] provides us with additional information on the physical mechanism and the parametric dependence of the anomalous particle inflow.[4] In particular, we find that the dependence of the density profiles on the line-average density, plasma current and toroidal field can be reproduced if we express the anomalous inward flux in terms of the collisionality parameter $\nu_e^{**} = \nu_{ei}Rq/V_{the}$. The relation between this particle transport model and the theory of the ion mixing mode[5] will be discussed.

*Supported in part by the United States Department of Energy.

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RADIAL EIGENMODE STABILITY FOR "BUMPILESS" EBT

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The radial eigenmode problem is of interest in the EBT device because there can be unstable modes localized within the thin hot electron annulus region. A model which facilitates analysis of the radial structure is the z-pinch, corresponding to a bumpiless, azimuthally symmetric version of EBT. With this model, we are able to reduce the coupled set of linear partial integro-differential mode equations (obtained from the momentum transfer equation with the anisotropic pressure calculated kinetically) to an ordinary differential equation in the radial direction.

By integrating across the annulus layer and matching inner and outer solutions, we analytically generate a fourth-order dispersion relation. One of the modes is low frequency and corresponds to the core plasma interchange, known to impose an upper limit on the allowed core pressure.[1] The three higher frequency modes provide additional stability limits on the core density and the annulus pressure. Taken together, these limits indicate that taking into account the radial mode structure leads to a more optimistic outlook for EBT stability.

Numerical solution of the radial differential equation with a shooting code yields results that are consistent with the analytic layer solution. Results for the radial profiles of the eigenmodes and their stability will be presented.

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3B34

MHD Stability of the Spheromak Configuration

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Ideal magnetohydrodynamic modes in a spheromak configuration can be classified according to whether or not they exist at zero pressure (current driven or pressure driven), and with a conducting wall at the plasma boundary (internal or free-boundary). Current driven internal modes are present if either the central q value is too low (peaked current) or the q profile is too flat (low shear). These are observed to saturate nonlinearly at a low amplitude without causing singular behavior in contrast to the ideal internal kink mode in a tokamak.[1] For profiles stable to current driven modes, pressure limits are set by internal mode stability to either Mercier ($m = \infty$) or $m = 1$, $n = 2$ modes. At low values of aspect ratio (small flux hole), $n = 1$ free boundary current driven tilting or shifting modes are the most dangerous. These can be stabilized by conducting strips in the vacuum region. The optimal location of these strips depends on the index of the externally supplied guide magnetic field. If the symmetry axis is vertical, vertical conductors will most effectively stabilize tilt modes, while horizontal conductors will stabilize shift modes.

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76-CH03073.

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Prefer Poster Session

CLASSICAL DIFFUSION AND TRANSPORT IN TORUS II

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The hydromagnetic equations, which describe the time evolution of a plasma undergoing energy transport through a sequence of axisymmetric equilibria, are transformed consistently into one-dimensional diffusion equations[1] in flux coordinates. The velocity components are eliminated. A computer code solving these equations has been used to study plasma diffusion and energy loss in Torus II. The field-related and geometric coefficients in the one-dimensional transport equations are evaluated from a two-dimensional equilibrium solver. The poloidal fluxes at the magnetic axis and on the wall surface are determined by the flux equation in volume coordinates. In the iterations between the 1-D and 2-D codes, we let the toroidal current density on fixed grid points float, so that the flux values at the magnetic axis and on the wall computed from the two codes match. Preliminary results using single-temperature and isotropic transport coefficients will be presented.

Work supported by US Dept. of Energy.

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Banana Drift Transport in Tokamaks with Ripple

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We discuss ripple transport in the "banana drift" collisionality regime, for which $\nu \ll \nu_*(Nq)^{-2} = \varepsilon^{3/2}v_T/N^2q^3R$. As a trapped particle executes its banana orbit, it experiences a ripple-induced radial drift that oscillates with the ripple phase. For particles in the banana drift regime, lying just below the ripple plateau in collisionality, the contributions to the radial drift average to zero except for the last ripples near each turning point. We calculate the transport coefficients, both heuristically and by solving the banana kinetic equation. The ambipolar thermal conductivity is shown to be

$$K^A = C\ nN \langle\delta^2\rangle\ \rho_\theta^2 \frac{v_T}{R} \frac{\nu_*}{\nu(Nq)^2}$$

where the toroidal field ripple is $B_o(\psi)\delta(\psi,\theta)\ \cos N\phi$, ρ_θ is poloidal gyroradius, and $\langle\delta^2\rangle$ denotes a specific weighted poloidal average of $\delta^2(\psi,\theta)$. The value of C is quite sensitive to the form of the high-energy tail of the distribution function.

For a Maxwellian, the form of our diffusion coefficient in this $1/\nu$ regime differs from that of earlier work [J. N. Davidson, Nucl. Fusion 16, 731 (1976); K. T. Tsang, Nucl. Fusion 17, 557 (1977)] essentially by a factor $(N^3q\varepsilon^2)^{-1}$, which for typical parameters is $10^{-2} - 10^{-3}$. The reasons for this difference are discussed.

The $1/\nu$ regime is cut off at lower collisionality by several effects including toroidal precession, which we treat in detail. Owing to a subtlety relating to the behavior of barely-trapped particles, the transport at low ν is in general found to go not as ν (as might be expected) but as ν^p where p is typically $\sim 0.5 - 1$.

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Interactions of Streaming Particles and Electromagnetic Ion Cyclotron Instability

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The left-handed circularly polarized ion cyclotron wave[1] is a transverse electromagnetic wave propagating parallel to the magnetic field. The wave is unstable if the ion temperature is anisotropic with $T_{i\perp} > T_{i\parallel}$.

The linear dispersion relation $\tilde{\omega} = \tilde{\omega}(K_{\parallel})$ of a homogeneous plasma is solved numerically, where $\tilde{\omega} = \omega/\omega_{ci}$ and $K_{\parallel} = k_{\parallel} c/\omega_{ci}$ respectively. There are two distinctive roots in the range of ion cyclotron frequencies. One is the unstable Alfven ion cyclotron wave (AIC); it is an Alfven wave at small values of $K_{\parallel}$ and asymptotic to the ion cyclotron frequency at larger values of $K_{\parallel}$. This mode is characterized by having a positive group velocity. The second root is a stable wave with negative group velocity. It is an ion cyclotron wave (IC) at small values of $K_{\parallel}$, and the mode frequency decreases as $K_{\parallel}$ increases. The modes intersect at a specific value of $K_{\parallel}$; the intersection is contrary to Nevins's prediction of coalescence in the fluid limit[2].

The dispersion relation changes drastically when the counter-streaming beams are introduced in the anisotropic background plasma. For beams with streaming energy above the threshold value, the AIC mode couples with the IC mode. The stable branch is the Alfven wave at small values of $K_{\parallel}$, and its mode frequency increases to a maximum and then decreases as $K_{\parallel}$ increases. The other branch is an ion cyclotron wave at small values of $K_{\parallel}$. This branch goes through a minimum frequency and then increases to the ion cyclotron range as $K_{\parallel}$ increases. This mode corresponds to the unstable wave and is driven by the anisotropic temperatures. Thus there exists a range of $\tilde{\omega}$ for which no waves propagate.

Details of this calculation and applications to the TMX are presented.

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1981 SHERWOOD THEORY MEETING

Austin, Texas - April 8-10, 1981

GLOBALLY RECONNECTING TEARING MODES IN THE REVERSED-FIELD PINCH*

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Globally reconnecting tearing modes are known to be of great importance in the tokamak both during the formation phase (double-tearing mode) and the steady-state phase (internal sawtooth oscillations) of operation. The possibility that appropriate analogs of such modes may be equally important to the operation of the Reversed-Field Pinch (RFP) is explored. In particular, such modes may be relevant to the startup phase where the RFP resembles a paramagnetic tokamak. We consider the generalization of the Kadomtsev reconnection model to the compressible case in toroidal flux coordinates. Both numerical and analytic solutions of this model are given. The importance of globally reconnecting tearing modes for the case of toroidal field reversal is considered. Some nonlinear numerical simulations are also presented.

*Work performed under the auspices of the USDOE.

POSTER SESSION REQUESTED

NUMERICAL SIMULATION OF THE BETA II EXPERIMENT*

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ABSTRACT

A code has been written to describe the evolution of the field-reversed mirror experiment, Beta II. The plasma and magnetic fields are assumed to be axisymmetric. The code alternates between a 2-D equilibrium calculation and the simultaneous solution of four 1-D transport equations. The transport equations include, (1) Braginskii transport coefficients, (2) collisional transfer of energy between ion and electrons, (3) Joule heating, (4) radiation cooling of electron due to impurity, (5) charge exchange loss of ion energy, (6) anomalous electron thermal conductivity. The code can also simulate the heating of the ions by a neutral beam.

After an initial transient the Joule heating of the electrons is approximately balanced by the radiation cooling due to impurities. The thermal conduction to the separatrix is small even when the electron conductivity is 100 times classical. The ion and electron temperatures remain approximately the same. The main energy source is the toroidal magnetic field. Energy is removed from the toroidal magnetic field and given to the electrons via Joule heating. The electrons then radiate the energy away. The number of particles lost during the calculation is small.

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*Prefer Poster Session

Effects Of Local Current Gradients On Magnetic Reconnection

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An analytical solution for the resistive magnetohydrodynamical equations across the dissipative layer and a detailed matching with the outer ideal MHD problem, in the framework of a generalized "constant-ψ" approach, show that reconnecting modes can be affected by the presence of current gradients at the singular surface.[1]

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Monte Carlo Simulation of Ion Transport in Analytical Tokamak and Stellarator Fields

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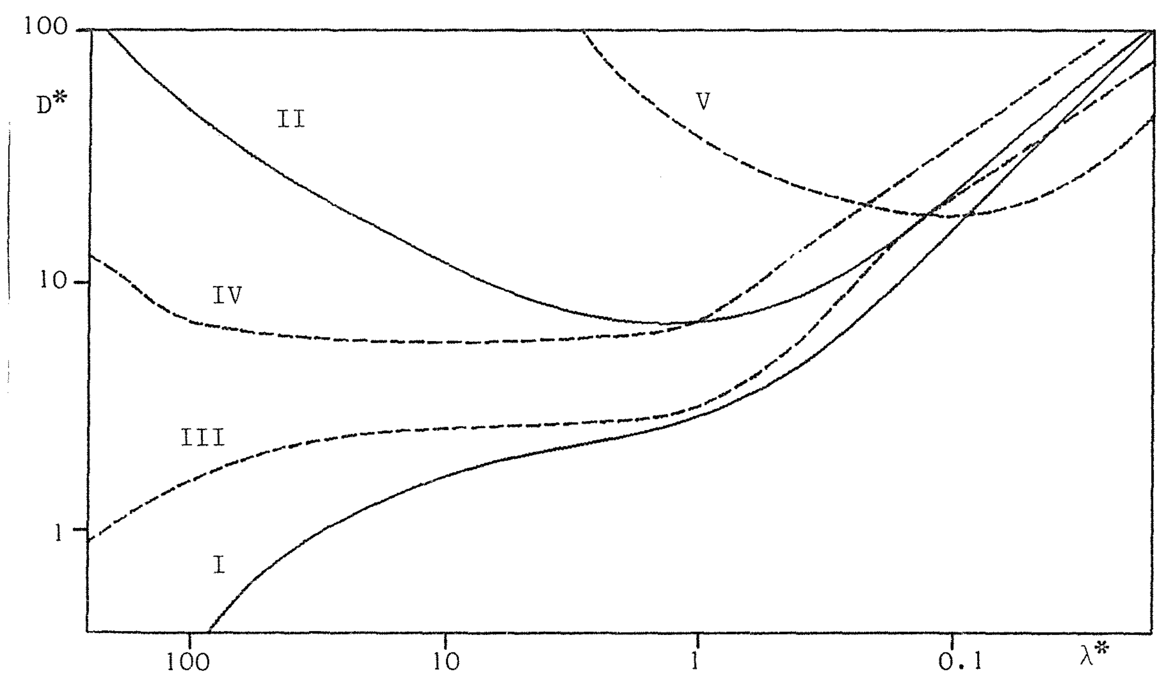
Analytical fields, in particular vacuum fields suitable for stellarators [1], are used for the Monte Carlo simulation of ion transport [2,3]. The figure shows results in terms of $D^*(\lambda^*)$, where $\lambda^* = \lambda/L_c$ (λ mean free path, $L_c = 2\pi R_T/\iota$ connection length) and $D^* = D\iota^2/r_i^{\,2}\nu_i(\lambda = L_c)$. I: Tokamak, aspect ratio A = 10, ι = .5; II: ℓ = 2 stellarator, number of periods N = 10, A = 10, ι = .5 (note that no saturation [2] of D^* occurs in the range considered); III: Tokamak, A = 40, ι = .8; IV: ℓ = 2 stellarator, A = 40, N = 10, ι = .8; V: ℓ = 1, 2 stellarator ([4], WAD 514) with significant reduction of parallel current density but without magnetic well and no emphasis on trapped particle drifts, A = 40, N = 10, ι = .8 (note that, as expected, the characteristic point is not $\lambda^* = 1$ but rather $\lambda^* = L_p/L_c$, where L_p is the period). The effects of a magnetic well, direct optimization of trapped particle behaviour (e.g. approximate omnigenity or symmetry), finite β and electrical field have still to be considered.



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SIMULATIONS OF ION CYCLOTRON RESONANCE HEATING IN TOKAMAKS[†]

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A study of ICRF heating of tokamak plasmas has been performed using 1-2/2D and 2-1/2D electromagnetic particle codes with absorbing boundaries. A two-ion species plasma (majority deuterium, 10% minority protons) is modeled with a uniform poloidal field and 1/R toroidal field, on a particular q surface. Ion cyclotron waves are excited on the low field side by antenas parallel either to the poloidal direction or to the toroidal direction. In 2D, minority ion heating ($v_\perp$) and electron heating ($v_\parallel$, $v_\perp$) are observed. The exponential electron heating seems due to a decay-type instability. The minority heating is consistent with mode conversion of fast Alfven waves and heating by electrostatic ion cyclotron waves. Minority heating is stronger with a poloidal antena. Slight majority heating above the collisional rate was also observed. The strong electron heating is accompanied by toroidal current generation. In 1D, no thermal instability was observed and only strong minority heating resulted as long as the conversion layer is not too wide. Because of the large memory requirement, the two-dimensional runs were carried out on the FACOM M-200 computer at Nagoya which can accommodate 4 times as many words as the CRAY-I.

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SELF-ADJOINTNESS OF THE VLASOV MAXWELL EQUATION

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In recent years numerical techniques have been used for the Vlasov-Maxwell equations based on the self-adjointness of the system. Generally self-adjointness is demonstrated for special cases but not from a general point of view. Here we show that the Vlasov-Maxwell integral operator with two ignorable coordinates, is self-adjoint (although not Hermetian). The operator is exact for all frequencies and wavelengths. In addition we obtain a representation that is a differential equation of arbitrarily high order that is manifestly self-adjoint. This representation should be useful in solving finite Larmor radius problems where truncation of the order is justifiable.

Alfven Wave Cyclotron Resonance Heating

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The propagation of Alfven waves in plasmas is of considerable interest, since under suitable conditions these waves can lead to significant plasma heating.[1,2] As the size of the plasma device increases, the coupling of the slow wave becomes increasingly difficult, and it would be more practical to launch a fast wave and have it absorbed by the plasma. We examine a primarily deuterium plasma with a small amount of hydrogen and explore the possibility of transmission from the the fast wave, which has a cutoff at the hybrid frequency, to the resonant branch, which is absorbed at the cyclotron resonance of the lighter ions. We examine parallel propagation with $N_\perp \ll 1$, unlike previous analyses.[3] We find that in the vicinity of the resonance the dispersion relation consists of a coupled fast wave and a damped Budden-like wave.[4,5] Using Laplace's method we find the general solution and calculate the transmission and reflection coefficients.

We find from an analysis of the linear resonance absorption that reasonable plasma heating can be expected through this mechanism.

Acknowledgment

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Poster Session

Magnetohydrodynamic Stability of Low-β Helically Symmetric Straight Equilibria

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ABSTRACT

The MHD stability of various classes of equilibria of straight helically symmetric plasma is considered.

The various equilibria are obtained from different scaling laws of the physical quantities with β which represents the plasma pressure and is considered to be a small parameter.

It can be shown that the potential energy is minimized by either a constant rotational transform, (μ), configuration or by highly localized modes. The latter case can give rise to ballooning like instabilities which are localized around a specific flux surface. This case is not treated here.

In the case of constant μ the combination of $\ell=2$ and $\ell=4$ helical windings is checked and found unstable to interchange type modes.

For possible stabilization ka is also considered to be small (k being the helical pitch parameter and a the plasma radius) and scaled as $\sqrt{\beta}$. This scaling gives rise to a family of equilibria which are characterized by $\Pi'(\chi) = P'(\chi)+\chi_o\chi_1'(\chi)$ where P is the plasma pressure and χ_o,χ_1 are the zero and first order in β components of the current flux function. A particular case, $\Pi'(\chi)=0$--the vacuum field, is investigated and a stability criterion is derived.

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Stellarator Equilibria at Finite Aspect Ratio

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Various stellarator expansions have hitherto been obtained for large aspect ratio by many authors. Here, a low-β stellarator expansion at finite aspect ratio is devised, which should be particularly suitable for the investigation of separatrix formation and its relation to the β-value. The MHD equilibrium equations are solved in the form

$$\vec{\nabla} \cdot \vec{B} = 0 \ (1), \quad \vec{B} \cdot \nabla F = 0 \ (2), \quad \vec{B} \cdot \nabla j = dp/dF \vec{\nabla} \cdot (\nabla F \times \vec{B}/B^2) \ (3),$$

$$\vec{j} = \vec{\nabla} \times \vec{B} \ (4)$$

where F describes the magnetic surfaces, j is related to the parallel current density, eq.(3) guarantees that $\vec{j}$ is divergencefree, so that eq.(4) is integrable. The following ordering is employed

$$\vec{B} = \vec{B}_o + \varepsilon \vec{B}_1 + \varepsilon^2 \vec{B}_2 + \ldots, \ \iota \sim O(\varepsilon^2), \ \beta \sim p/B^2 \sim O(\varepsilon^4) \ .$$

Eq.(1) is satisfied with (r, φ, z cylindrical coordinates)

$$\vec{B}_o = \nabla\psi \times \nabla\chi \ , \quad \psi = -\ell n \ r \ , \quad \chi = z$$

$$\vec{B}_\nu = \nabla u_\nu \times \nabla\psi - \nabla v_\nu \times \nabla\chi \ , \quad \nu \geq 1$$

where $\vec{B}_1$ is the curlfree stellarator field with single-valued u_1, v_1 perturbing the main toroidal field $\vec{B}_o$, and $\vec{B}_2$ is axisymmetric and meridional

$$\vec{B}_2 = (U_r \nabla z - U_z \nabla r)/2\pi r \ , \quad U = U(r, z)$$

where U is related to j_2 by

$$j_2 = -\Delta^* U/2\pi \ , \quad \Delta^* = \partial_{rr} + \partial_{zz} - \frac{1}{r}\partial_r$$

The axisymmetric zeroth order flux surfaces solving eq.(2) can be obtained explicitly [1]

$$F_o = -U/2\pi + \langle u_{1,\varphi} v_1 \rangle \ , \quad \langle \ldots \rangle = \int_o^{2\pi} \ldots \, d\varphi/2\pi \ .$$

The equation for F_o is obtained from the fourth-order integrability condition of eq.(3)

$$\Delta^*(F_o - \langle u_{1,\varphi} v_1 \rangle) + r^2 \, dp/dF_o + f \, df/dF_o = 0$$

which is the desired low-β stellarator equilibrium relation for finite aspect ratio.

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Ballooning Modes in Low-β Stellarators

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The ballooning criterion for non-axisymmetric configurations [1] can be written in the form

$$\vec{B}\cdot\nabla(E\vec{B}\cdot\nabla f) + Df = 0,\quad E = \vec{A}^2/B^2,\quad \vec{A} = \dot\Phi\nabla\Theta - \dot\chi\nabla\zeta + z\nabla v,$$
$$z = \zeta(\dot\chi\ddot\Phi - \dot\Phi\ddot\chi)/\dot\Phi,\ D = \dot p\ddot\Phi/\dot\Phi + \dot p^2/B^2 + \vec{B}\cdot\nabla d,\ d = \dot p\vec{B}\cdot(\vec{A}\times\nabla\zeta)/(\dot\Phi B^2), \tag{1}$$

where Θ, ζ, v are Hamada coordinates. The system is unstable if eq.(1) has regular solutions f with two zeros. Equilibria with the following ordering are considered (small rotational transform):

$$\vec{B} = \vec{B}_o + \varepsilon\vec{B}_1 + \ldots;\ \dot\chi \sim O(\varepsilon^2);\ \dot p \sim O(\varepsilon^4);$$
$$\nabla\Theta, \nabla v \sim O(1);\quad \nabla\zeta \sim O(\varepsilon^{-2}). \tag{2}$$

Eq.(1) can be treated with a two-scale method (see, for example, [2]) by assuming $z \sim O(1)$, $\vec{B}_o\cdot\nabla z \sim O(\varepsilon^2)$. Then $A, E \sim O(1)$; $d, D \sim O(\varepsilon^2)$, and the series

$$\dot p = \varepsilon^4\dot p_4 + \ldots,\ d = \varepsilon^2 d_2 + \ldots,\ E = E_o + \ldots,$$
$$f = f_o(z) + \varepsilon^2 f_2(z,\zeta) + \varepsilon^3 f_3(z,\zeta) + \ldots$$

yields in fourth order of eq.(1) (ζ-periodicity of $f_4(z,\zeta)$)

$$\left[\left\langle\frac{1}{E_o}\right\rangle^{-1} f_o'\right]' + \left[\dot p_4\frac{\ddot\Phi_o}{\dot\Phi_o} + \left\langle\frac{d_2^2}{E_o}\right\rangle - \left\langle\frac{d_2}{E_o}\right\rangle^2\left\langle\frac{1}{E_o}\right\rangle^{-1} + \left(\left\langle\frac{d_2}{E_o}\right\rangle\left\langle\frac{1}{E_o}\right\rangle^{-1}\right)'\right] f_o = 0, \tag{3}$$

where $\ldots' = (\dot\chi_2\ddot\Phi_o - \dot\Phi\chi_2)d/dz$, and $\langle\ldots\rangle$ is the average on the closed field lines of $\vec{B}_o$. Thus, with the scaling (2), the ballooning stability condition reduces to eq.(3), which only contains the slow secular variable z. If, in addition, $\vec{B}_o$ is the axisymmetric toroidal vacuum field, then the low-β stellarator equilibrium problem reduces to a formally axisymmetric one, so that the averages are trivial and the z-dependence of the coefficients of eq.(3) is explicitly known. For vanishing longitudinal current condition (3) can be compared with a sufficient criterion [3] for external modes which for the scaling (2) yields

$$-\dot p(\dot\Phi\ddot\Phi + \dot p\langle|\nabla\zeta|^2\rangle) \geqq 0\ . \tag{4}$$

Condition (4) is always more stringent than eq.(3), as it has to be.

[1] Correa-Restrepo, D., Z.Naturforsch.33a (1978), 789
[2] Lortz, D., Nührenberg, J., Nucl.Fusion 19 (1979) 1207
[3] Lortz, D., Rebhan, E., Spies, G., Nucl.Fusion 11 (1971) 583

Omnigenous Stellarators

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Omnigenous configurations [1] were hitherto investigated with regard to mirror equilibria [2]. Here, it is shown that locally omnigenous stellarators exist, i.e. periodic 3D-MHD equilibria with rotational transform, vanishing net longitudinal current and

$$(\vec{B} \times \nabla\psi) \cdot \nabla B^2 = 0 \tag{1}$$

(ψ flux surface) so that the guiding centre drift lies in the magnetic surfaces. For the proof, straight vacuum field configurations are considered in the thin-tube approximation. In order that eq.(1) be satisfied the following set of equations has to be solved:

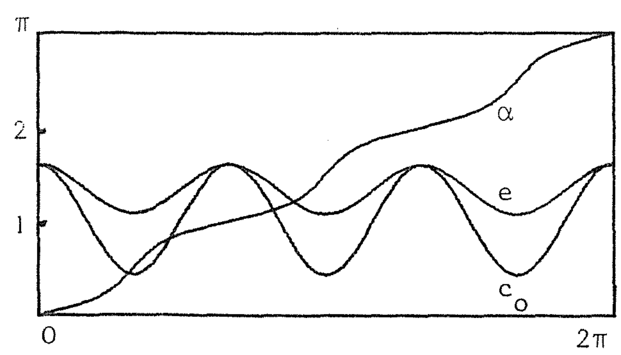
$$\alpha' = \alpha_o' \, c_o(e^2+1)e/(e^2-1)^2$$

$$\alpha_o' = \frac{\pi}{L_p} \langle c_o(e^2+1)e/(e^2-1)^2 \rangle^{-1}$$

$$\left[\frac{e^2+1}{e^2-1}\frac{e'}{e} - \frac{c_o'}{c_o}\right]' + \frac{1}{2}\left(\frac{c_o'}{c_o} - \frac{e^2+1}{e^2-1}\frac{e'}{e}\right)^2 + 2\frac{e'^2}{e^2}\frac{e^2}{(e^2-1)^2}$$

$$- 2\alpha_o'^2 e^2 \frac{e^4+6e^2+1}{(e^2-1)^4} c_o^2 = 0$$

where e is the half-axes ratio of the elliptical plasma cross-section, α is the turning angle $[\alpha(L_p) - \alpha(0) = \pi]$, and c_o is the magnetic field on axis.



Periodic mirror equilibria ($\alpha_o' = 0$) do not exist, while solutions exist for stellarators, at least if the length scales of e, c_o are decoupled from the turning rate, as is seen from the example in the figure. Toroidal versions are at least possible if many periods are admitted.

[1] Hall, L.S., McNamara, B., Phys.Fluids 18 (1975) 552
[2] Catto, P.J., Hazeltine, R.D., Bulletin APS 25 (1980) 7Q15 and SAI-254-81-009-LJ, PRI-21