# 1983 SHERWOOD THEORY MEETING

## March 21-23, Arlington, Virginia

Hosted by:

Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

1983 SHERWOOD THEORY MEETING

ANNUAL CONTROLLED FUSION THEORY CONFERENCE

March 21-23, 1983
Arlington, Virginia

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|---|---|---|
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| P. C. Liewer | R. Moses, Jr. | M. Dolan |
| D. Nicholson | W. Nevins | J. Finn |
| R. A. Nebel | D. Schnack | C. Grebogi |
| T. M. O'Neil | H. Strauss | B. Krusberg |
| W. L. Sadowski | | A. Monroe |
| R. Waltz | | D. Winske |
| H. Weizner | | |

# SCHEDULE

## Sunday, March 20, 1983

6:00 - 10:00 p.m. -- Registration
8:00 - 10:00 p.m. -- Reception

## Monday, March 21, 1983

8:15 - 8:30 -- Welcome

| Oral Sessions | | Poster Sessions | |
|---|---|---|---|
| 1A | 8:30 - 9:20 (Review Paper) | | |
| 1B | 9:20 - 9:45 * | 1P | 9:30 - 10:45 |
| 1C | 10:30 - 12:15 | 1Q | 11:00 - 12:15 |

12:15 - 2:00 -- Lunch

| | | | |
|---|---|---|---|
| 1D | 2:00 - 3:15 | 1R | 2:00 - 3:45 ** |
| 1E | 3:45 - 5:00 | 1S | 4:00 - 5:45 |

## Tuesday, March 22, 1983

| Oral Sessions | | Poster Sessions | |
|---|---|---|---|
| 2A | 8:30 - 9:20 (Review Paper) | | |
| 2B | 9:20 - 9:45 * | 2P | 9:30 - 10:45 |
| 2C | 10:30 - 12:15 | 2Q | 11:00 - 12:15 |

12:15 - 2:00 -- Lunch

| | | | |
|---|---|---|---|
| 2D | 2:00 - 3:15 | 2R | 2:00 - 3:45 ** |
| 2E | 3:45 - 5:00 | 2S | 4:00 - 5:45 |

## Wednesday, March 23, 1983

| Oral Sessions | | Poster Sessions | |
|---|---|---|---|
| 3A | 8:30 - 9:45 * | 3P | 8:30 - 10:15 |
| 3B | 10:30 - 12:15 | 3Q | 10:30 - 12:15 |

* Coffee, tea, Sanka, and Danish pastries will be available from 9:45 - 11:00 a.m.
** Beer and soft drinks will be available from 3:15 - 5:00 p.m.

## GENERAL INFORMATION

There were 286 papers submitted, of which 29 were selected for oral presentation.

All oral sessions will be held in the Potomac Ballroom. Each talk will be 20 minutes in length plus 5 minutes for discussion.

All other functions will take place in the Third Floor Conference Suites: the Jackson, Madison, Adams, Lincoln, Washington, Jefferson, and Monroe rooms.

Poster sessions will be held in the Jackson, Madison, Adams, and Lincoln rooms.

Soft drinks and beer will be served in the Washington room across from the posters.

The Jefferson room is available as a hospitality room.

Any requests for special meetings should be made with D. Brosius at the meeting registration desk. These meetings will be held in the Monroe Room.

1983 SHERWOOD MEETING
THEORETICAL ASPECTS OF CONTROLLED THERMONUCLEAR RESEARCH
MARCH 21-23, 1983

SUNDAY MARCH 20

6:00 - 10:00 p.m. REGISTRATION
8:00 - 10:00 p.m. RECEPTION

MONDAY MARCH 21

7:30 - 5:00 REGISTRATION

8:15 - 8:30 WELCOME

8:30 - 9:20 ORAL SESSION 1A POTOMAC BALLROOM

1A1. R. Goldston. Review Paper: Recent Confinement Studies in Tokamaks with Ohmic and Auxiliary Heating.

9:20 - 9:45 ORAL SESSION 1B POTOMAC BALLROOM

1B1. Equilibrium and Stability Properties of High Beta Torsatrons. B. A. Carreras, W. A. Cooper, L. Garcia, T. C. Hender, H. C. Hicks, J. A. Holmes, and V. E. Lynch.

10:30 - 12:15 ORAL SESSION 1C POTOMAC BALLROOM

1C1. Formation of Energetic Tail Ion Species During the Negative Potential Operation in EBT. C. S. Chang, G. E. Guest, R. L. Miller, and R. A. Dandl.
1C2. Drift-Alfven Modes in High Current Pinches. C. Chu, W. Bard, R. Moore, and Y. C. Lee.
1C3. Confining Potential in a Thermal-Barrier Tandem Mirror with Strong ECRH in the Plugs. R. H. Cohen, Y. Matsuda, and J. W. Shearer.
1C4. Turbulent Relaxation of Compressible Plasmas with Flow. J. M. Finn and T. M. Antonsen, Jr..

9:30 - 10:45 POSTER SESSION 1P THIRD FLOOR CONFERENCE SUITES

1P1. Collisionless Drift and Tearing Modes in a Plasma Cylinder with Magnetic Shear. J. R. Cary and B. S. Newberger.

1P2. Three-Dimensional MHD Equilibria Obtained Using the Inverse Spectral (Moment) Method. J. C. Whitson and S. P. Hirshman.
1P3. Computation of Field-Reversed Theta-Pinch Equilibria. D. C. Stevens, E. Hameiri, and W. Grossmann.
1P4. Particle Simulation Study of Drift Wave Turbulence. R. D. Sydora, J.-N. Leboeuf, T. Tajima, and P. H. Diamond.
1P5. Particle Simulation of Drift Instabilities. J. N. Leboeuf, R. D. Sydora, and T. Tajima.
1P6. Sharp Boundary Equilibria in Tandem Mirrors. L. D. Pearlstein.
1P7. Dynamo Action from Stable Alfven Waves. R. A. Nebel, T. Hewitt, K. A. Werley, and G. H. Miley.
1P8. 3D Calculations of Self-Consistent Electrostatic and Magnetostatic Equilibria in Tandem Mirrors. D. V. Anderson and M. E. Rensink.
1P9. Stochastic Electron Heating Due to ICRH in EBT-S. G. L. Chen and D. B. Batchelor.
1P10. Fokker-Planck Investigations of RF Current Drive. D. W. Hewett, V. Krapchev, J. P. Freidberg, and A. Bers.
1P11. A Theory of the Relaxation of Tokamak Discharges. J. E. Brandenburg.
1P12. Shear Alfven Waves in Tokamaks. C. Z. Cheng, L. Chen, and M. S. Chance.
1P13. Analytic Resistive Shear Alfven Wave Spectrum in a Cylinder. G. Marklin.
1P14. Effect of the Ambipolar Potential on the Confinement of Reactor-Scale Stellarators. W. N. G. Hitchon and H. E. Mynick.
1P15. Kinetic Effects and Stabilization of Flute Instability in Sheared Magnetic Fields. K. Nakamura and J. M. Dawson.
1P16. Resistive Axisymmetric Evolution of the Bean Tokamak. S. C. Jardin and M. Okabayashi.
1P17. Collisionless Internal Kink Modes. G. B. Crew, B. Coppi, J. Martinell, and J. J. Ramos.
1P18. Comparison of MHD Equilibrium Calculations Using the Stellarator Expansion. G. Rewoldt, J. L. Johnson, and J. A. Holmes.
1P19. The Impact of the Ring Electron Distribution on the Stability of EBT. K. Nguyen and T. Kammash.
1P20. Coupling Theory of the JET ICRH Antenna. K. Theilhaber.
1P21. Drift Wave Turbulence and Shielding. P. Similon and P. H. Diamond.
1P22. Fat Bananas in EBT. D. E. Hastings.
1P23. Extensions of the ORNL EBT Monte Carlo Diffusion Code. J. S. Tolliver, E. F. Jaeger, D. E. Hastings, and C. L. Hedrick.
1P24. Sensitivity of Global Confinement Properties in EBT to the Existence of an Ambipolar Potential Well. E. F. Jaeger.
1P25. Ray Tracing Analysis of the Lower Hybrid Experiment on the Wisconsin Octupole. R. C. Goldfinger and T. L. Owens.
1P26. Finite Larmor Radius Effects on Stability and Heating of Screw- and Reversed-Field Pinches. H. R. Lewis, T. Hewitt, J. P. Mondt, and J. Tataronis.

11:00 - 12:15 POSTER SESSION 1Q THIRD FLOOR CONFERENCE SUITES

1Q1. Gyroscopic Stabilization of a Spheromak Plasma Configuration. R. Olson, B. Saoutic, and C. Choi.
1Q2. Stabilization of Trapped Particle Modes in the Tara Tandem Mirror. J. Kesner and B. Lane.
1Q3. Gyrokinetic Particle Simulation and Nonlinear Drift Waves. W. W. Lee, J. A. Krommes, R. Smith, and C. Oberman.
1Q4. Energy Losses by Thermal Conduction in Field-Reversed Configurations. M. Tuszewski.
1Q5. Multipole Stabilization of Field-Reversed Configurations: A Whole Lotta Shakin' Goin' On. R. L. Spencer.
1Q6. Hopf Bifurcation in Kinetic Theory: Application to a Collisional Beam-Plasma Instability. J. D. Crawford.

1Q7. Helical Axis Stellarators with Planar, Nearly Circular Coils. A. Reiman and A. H. Boozer.
1Q8. Effects of Magnetic Shear on the Current-Driven Drift-Alfven Instability. N. T. Gladd and N. A. Krall.
1Q9. Monte Carlo Orbit Calculations in ATF. J. A. Rome, R. H. Fowler, and J. F. Lyon.
1Q10. Total Radiation from Argon Edge Plasmas. J. P. Dinguirard and D. Mostacci.
1Q11. Drift Pumping at Bounce Resonance Frequencies in Tandem Mirrors. J. A. Byers, Y.-J. Chen, and D. E. Baldwin.
1Q12. FLR Modification of the Variational Form of the Eigenmode Eq. for EM Perturbation of Inhomogeneous Magnetized Plasmas. H. V. Wong.
1Q13. Spectral Properties of the Kinetic Alfven Wave in Tokamak Geometry. G. Vahala, D. J. Sigmar, and Y-T. Yan.
1Q14. An Analytical Calculation of the Trapping Rate in Thermal Barriers. X. Z. Li and G. A. Emmert.
1Q15. Vlasov Stability of a One-Dimensional Field-Reversed Theta Pinch. J. L. Schwarzmeier, H. R. Lewis, T. G. Hewitt, and C. E. Seyler.
1Q16. Quasistatic Evolution and Stability of a Compact Toroid. A. G. Sgro and G. Marklin.
1Q17. Theoretical Modeling of ICRF in Reactor Size Plasmas. R. J. Kashuba, P. L. Colestock, and J. F. Pipkins.
1Q18. Linear and Nonlinear Study of Ideal Internal Kink Modes. R. Izzo, D. A. Monticello, W. Park, J. Manickam, H. R. Strauss, R. Grimm, J. Delucia, and K. McGuire.
1Q19. Group Theory Approach to the One-Dimensional MHD Equations. J. Gross.
1Q20. A Generalized Fokker-Planck Equation: The Inclusion of the Nuclear and Coulomb-Nuclear Interference Cross Sections. A. Andrade and G. M. Hale.
1Q21. Nonlinear Fluid Models for Tokamak Plasma Dynamics. R. D. Hazeltine, M. Kotschenreuther, and P. J. Morrison.
1Q22. Some Comments on the Minimum Energy Helical State for Reversed-Field Pinches. C. K. Chu.
1Q23. Time-Dependent Hydrodynamic Plasma-Well Calculations. D. Morrison and R. Morse.
1Q24. Stationary Wall Plasma Structures in the Lower Temperature, Fluid Model Regime. G. Sowers, D. Morrison, and R. Morse.
1Q25. Long-Time Behavior for Inverse Cascades in Finite Systems. M. Hossain, W. H. Matthaeus, and D. Montgomery.
1Q26. Drift Rippling Modes. L. Garcia, B. A. Carreras, and H. R. Hicks.

12:15 - 2:00 LUNCH

2:00 - 3:15 ORAL SESSION 1D POTOMAC BALLROOM

1D1. Alfven Ion-Cyclotron Instability in Tandem-Mirror Plasmas. G. R. Smith, W. M. Nevins, and W. M. Sharp.
1D2. MHD Equilibrium and Stability of Finite Beta Tandem Mirrors. H. Strauss and D. S. Harned.
1D3. A Comparative Study of a d-d and a d-t Tandem Mirror. D. Dobrott, H. Gurol, and G. W. Shuy.

## 3:45 - 5:ØØ ORAL SESSION 1E     POTOMAC BALLROOM

1E1. Structures of Wall Plasmas Near Divertor Neutralizer Plates and Limiters. R. Morse, P. Gierszewski, J. McCullen, and P. McKenty.
1E2. Parametric Instabilities During Electron Cyclotron Heating of Tandem Mirrors. D. R. Nicholson.
1E3. A New Long Mean Free Path Resistive MHD Instability. J. D. Callen and K. C. Shaing.

## 2:ØØ - 3:45 POSTER SESSION 1R     THIRD FLOOR CONFERENCE SUITES

1R1. Linear and Nonlinear Numerical Studies of Magnetic Fluctuations in ETA-BETA-II. D. C. Baxter and D. D. Schnack.
1R2. Unstable-Unstable Pair Bifurcation and Chaotic Transients. C. Grebogi, E. Ott, and J. A. Yorke.
1R3. Fractal Basin Boundaries. S. McDonald, C. Grebogi, E. Ott, and J. A. Yorke.
1R4. Three Dimensional Ballooning Mode Stability for Stellarators. H. L. Berk, M. N. Rosenbluth, and J. L. Shohet.
1R5. Force-Free Hydromagnetic Equilibria of 3-D Configurations. M. P. Bernardin and J. A. Tataronis.
1R6. ECRH Induced Parametric Instabilities in Tokamaks. B. Levush, T. M. Antonsen, Jr., and E. Ott.
1R7. Drift Surface Studies of EBT Configurations with Noncircular Magnetic Coils. R. L. Miller.
1R8. Simulation of Drift-Cyclotron-Loss-Cone Modes in Tandem Mirrors with Sloshing Ions. B. I. Cohen and N. Maron.
1R9. Finding of a "Bremsstrahlung Cortex" in Advanced Fuel Burning Plasmas. G. Vlad and B. Coppi.
1R1Ø. Tokamak Reactor Startup. K. M. Ling, S. C. Jardin, and F. W. Perkins.
1R11. Near Integrable Vacuum Magnetic Fields in Stellarator Geometry. J. D. Hanson and J. R. Cary.
1R12. Nonlinear Magnetohydrodynamics of a Three-Dimensional Cylindrical RFP. D. D. Schnack.
1R13. Density Threshold for Parametric Instability of Lower Hybrid Waves in a Tokamak. C. S. Liu, V. S. Chan, V. K. Tripathi, and V. Stefan.
1R14. Halo Plasma Physics Model for Mirror Machines with Neutral Beam Injection. J. F. Santarius.
1R15. Extensions of the Theory for Neutral-Beam Driven Impurity Flow Reversal. W. M. Stacey, Jr..
1R16. MHD Simulation of Maryland Spheromak Formation. K. W. Whang and J. M. Finn.
1R17. Effects of Toroidal Rotation and Pressure Anisotropy on Tokamak Equilibria. L. L. Lao, W. A. Cooper, R. M. Wieland, and F. J. Helton.
1R18. Ion-Beam-Driven Electrostatic Ion Cyclotron Instabilities. K.-I. Nishikawa and H. Okuda.
1R19. Compressional Alfven Waves for Heating and Current Drive. D. W. Ross, S. M. Mahajan, and Y. M. Li.
1R2Ø. Ripple Penetration in High and Low Beta, Resistively Diffused Tokamaks. L. Ibanez, A. Bayliss, and H. Grad.
1R21. Stability of the Hot-Electron Mode in EBT. Y. Ohsawa and J. M. Dawson.
1R22. Combined Electron Cyclotron Heating and Lower Hybrid Current Drive. V. S. Chan, C. S. Liu, F. W. McClain, and M. Rosenberg.
1R23. Saturated Tearing Modes in Toroidal Geometry. R. N. Morris and G. Bateman.
1R24. Ideal Marginal Magnetohydrodynamics. R. L. Dewar.
1R25. Spectral-Method Computation of Viscous, Resistive MHD Stability. R. B. Dahlburg, T. A. Zang, D. Montgomery, and M. Y. Hussaini.
1R26. Turbulent Behavior of the Strauss Equations. W. H. Matthaeus and D. Montgomery.

4:00 - 5:45 POSTER SESSION 1S     THIRD FLOOR CONFERENCE SUITES

1S1. Simulations of the Density, Phase, and Toroidal Field Dependence of Lower Hybrid Current Drive. R. Englade and P. Bonoli.
1S2. Resistive Ballooning Modes. R. W. Moore and M. S. Chu.
1S3. Ion Skin Depth Scaling in the Toroidal Cusp Experiment. S. T. Ratliff and J. M. Dawson.
1S4. An Integral Formalism for Electromagnetic Perturbations in a Low Beta Plasma. Application to High M Drift-Tearing Modes. R. Farengo, Y. C. Lee, and P. N. Guzdar.
1S5. An Estimate of the Figure-of-Merit for the Two-Step Approach to Steady-State Current Drive in Tokamaks Using Electron Cyclotron Heating G. E. Guest.
1S6. Kinetic and Fluid Ballooning Stability in Anisotropic Ion Tokamaks. W. A. Cooper.
1S7. Unified Field Theory of Discrete and Collective Gyroresonant Wave-Particle Interaction in Complex Geometry. A. N. Kaufman.
1S8. Resistive Modes in Reversed Field Pinches. J. A. Holmes, B. A. Carreras, T. C. Hender, H. R. Hicks, V. E. Lynch, and B. F. Masden.
1S9. Beta Limits Imposed by High-n Ballooning Modes. A. Sykes and M. F. Turner.
1S10. Low Frequency Heating of a Resistive Doublet, Continued. M. Kress and H. Grad.
S11 Degradation of Electron Energy Confinement Properties in the Presence of Auxiliary Heating. M. Mars, P. T. Bonoli, B. Coppi, and R. C. Englade.
1S12. Reversed Field Plasma Configurations in the Upper Atmosphere. J. R. McNally, Jr..
1S13. Scattering and Stochasticity of Electrons Interacting with Coherent Wavepackets. V. Fuchs, V. Krapchev, A. Ram, and A. Bers.
1S14. The Renormalization Group Applied to Nonlinear Mapping. A. B. Rechester.
1S15. Point Model Calculation of MFTF-B. R. A. Jong, J. W. Shearer, and M. E. Rensink.
1S16. Initial Startup of a Tandem Mirror Reactor. M. A. Firestone and R. W. Conn.
1S17. Ambipolar Potential in Tokamak Plasma with Time-Dependent Magnetic Fluctuations. R. W. Harvey.
1S18. Limits on the Construction of Numerical Equilibria Using the Stellarator Expansion Technique. H. R. Hicks, B. A. Carreras, J. A. Holmes, V. E. Lynch, and B. F. Masden.
1S19. Internal Kinks and Fishbones. D. Monticello, H. Strauss, R. Izzo, W. Park, K. McGuire, and R. White.
1S20. Fast Ion Thermalization and Confinement in TF-Rippled Tokamak Reactors. L. M. Hively.
1S21. Evaluation of Mercier's Criterion in the WVII-AS Stellarator. R. Grossmann, F. Herrnegger, and J. Nuehrenberg.
1S22. Tearing Modes and the Parallel Electric Field Boundary Condition. G. Craddock, R. Hazeltine, and S. Mahajan.
1S23. Magnetic Fluctuations in High-Beta Circular and Noncircular Tokamak Discharges. J. K. Lee, L. C. Bernard, M. S. Chu, F. J. Helton, R. Izzo, and W. Park.
1S24. Confinement Effects of Electron Heating on the Thermal Barrier of a Tandem Mirror. P. J. Catto and R. Carrera.
1S25. Collisional Boundary Layer Effects on the Thermal Barrier Ion Trapping Rate of a Tandem Mirror. R. Carrera and J. D. Callen.
1S26. Determination of a Value for the Anomalous Electron Thermal Conductivity. D. Humphreys and L. Sugiyama.

## TUESDAY MARCH 22

### 8:30 - 9:20 ORAL SESSION 2A

2A1. E. B. Hooper. Review Paper: Tandem Mirror Experiments: Results and Comparison with Theory.

### 9:20 - 9:45 ORAL SESSION 2B

2B1. Modeling of ICRF Heating of a Tokamak Plasma. D. Q. Hwang, C. F. F. Karney, J. C. Hosea, J. M. Hovey, C. E. Singer, and J. R. Wilson.

### 10:30 - 12:15 ORAL SESSION 2C

2C1. A Fokker-Planck Equation for Spin-Polarized Particles. S. Cowley, R. M. Kulsrud, and E. Valeo.
2C2. Instability of Fusing Plasmas and Relevant Spin-Depolarization Process. B. Coppi, F. Pegoraro, and J. J. Ramos.
2C3. Energetic Particle Stabilization of Ballooning Modes in Tokamaks. M. N. Rosenbluth, S-T. Tsai, J. W. Van Dam, and M. Engquist.
2C4. Stability of Bean-Shaped Tokamak Equilibria Against Localized MHD Modes. M. S. Chance, R. C. Grimm, and J. Manickam.

### 9:30 - 10:45 POSTER SESSION 2P

2P1. A Kinetic Model of Plasma Flow to Divertors and Limiters. A. W. Bailey and G. A. Emmert.
2P2. Plasma Transport in High Density Divertors. C. Singer, W. Langer, M. Petravic, and D. Post.
2P3. Monte-Carlo Simulation of the ISX Pumped Limiter. K. Evans, Jr., D. Heifetz, D. Post, and P. Mioduszewski.
2P4. Neutral-Particle Transport in the PDX Scoop Limiter and the ALT-I Limiter. C. D. Boley, D. B. Heifetz, D. E. Post, R. V. Budny, and R. J. Knize.
2P5. Stabilization of Axisymmetric Mirrors by an Energetic Ion Beam. C. E. Seyler, J. F. Krall, L. C. Sparks, and R. N. Sudan.
2P6. Neoclassical Transport in a Multiple Helicity Torsatron in the Low Collisionality Regime. K. C. Shaing.
2P7. Linear and Nonlinear Studies of Resistive Interchange Modes in a Reversed Field Pinch. A. A. Mirin and N. J. O'Neill.
2P8. Intensity Correlations of Plasma Radiation. T. M. Sutton.
2P9. Gyrokinetic Algorithm for Perturbed Distribution Using the Characteristic Orbit. T. Tajima and F. W. Perkins.
2P10. Stabilization of External Ideal MHD Kinks by Means of a Limiter. J. P. Freidberg, J. P. Goedbloed, and R. Rohatgi.

2P11. Numerical Studies of Electric Field and Radio-Frequency Wave Driven Run-Away Electrons. E. Moghaddam-Taaheri, K. Papadopoulos, H. L. Rowland, and L. Vlahos.
2P12. A Nonlinear Theory for the Ohm-Navier-Stokes System of Dissipative MHD. Z. Yoshida and Y. Giga.
2P13. Studies in Ohmic Heating in the Spheromak. R. E. Olson and G. H. Miley.
2P14. Practical Aspects of Amplitude Transport in Ray Tracing Calculations. T. M. Smith.
2P15. Stability of a Poloidal Control System for Large Tokamaks. T. H. Jensen and F. W. McClain.
2P16. Current and Particle Density Effects on Ignition in the Presence of Sawteeth. L. Sugiyama.
2P17. Stochastic Particle Acceleration Induced by Low Amplitude Wave in an Inhomogeneous Magnetic Field. S. Riyopoulos, E. Ott, and T. M. Antonsen, Jr..
2P18. EBT Stability for Arbitrary m-Number and Radial Profile. K. Cogswell and J. P. Freidberg.
2P19. Propagation and Absorption of Electromagnetic Waves in Fully Relativistic Plasmas. D. B. Batchelor, R. C. Goldfinger, and H. Weitzner.
2P2Ø. Quasilinear Evolution of the Self-Filamentation Mode. A. B. Hassam.
2P21. Stellarator Transport Modeling. W. A. Houlberg, J. F. Lyon, and K. C. Shaing.
2P22. Nonlinear Evolution of Divertor Discharges. W. Park, R. Izzo, J. K. Lee, K. McGuire, D. A. Monticello, H. R. Strauss, and R. B. White.
2P23. Rotational and Kinetic Effects on Ballooning Modes in Tandem Mirrors. G. L. Francis, X. S. Lee, and P. J. Catto.
2P24. A Cross-Field Streaming Instability with Electron Temperature Anisotropy in Tandem Mirrors. J. D. Gaffey, Jr., M. Tanaka, and S. T. Tsai.
2P25. Sputtering Rates of Divertor Neutralizer Plate and Limiter Surfaces. P. McKenty, P. Gierszewski, J. McCullen, and R. Morse.
2P26. Transport Theory for Turbulent Plasmas: Microscopic Reversibility, the Onsager Relations, and Broken Symmetry. K. Molvig and K. Hizanidis.

11:ØØ - 12:15 POSTER SESSION 2Q

2Q1. Finite Orbit Analysis for Long Wavelength Modes in a Plasma with a Hot Component. J. H. Hammer and H. L. Berk.
2Q2. BAL - A Balloon Code for the 8Ø's. A. H. Glasser.
2Q3. Relativistic 2-Dimensional Theory of Lower-Hybrid Current Drive. K. Hizanidis, V. Krapchev, and A. Bers.
2Q4. Diffusion of Transiently Trapped Test Particles. H. A. Rose.
2Q5. Numerical Studies of the Collisional Drift Wave in Toroidal Geometry. P. C. Liewer and L. Chen.
2Q6. Arresting the Ballooning Mode. D. J. Elkin and S. Johnston.
2Q7. Effect of Magnetic Bending on the EBT High Frequency Stability. H. F. Hassan, H. A. Kirolous, and A. M. El Nadi.
2Q8. Radial Structure of Drift Cyclotron and DCLC Eigenmodes in Cylindrical Geometry. R. G. Littlejohn.
2Q9. MHD Equilibria with Helical Symmetry in the Presence of Purely Helical Flow. Y. Z. Agim, L. C. S. Goes, and J. A. Tataronis.
2Q1Ø. Tokamak Ripple Transport, Revisited. H. E. Mynick and W. N. G. Hitchon.
2Q11. Plateau Regime Transport for Plasmas with Strong Toroidal Rotation. D. J. Sigmar and K. C. Shaing.
2Q12. Toroidal Momentum Confinement in Beam Heated Tokamaks. J. T. Hogan.
2Q13. Fokker-Planck Calculations for Hot Electron Startup in MFTF-B. Y. Matsuda, G. D. Porter, J. W. Shearer, J. J. Stewart, and P. A. Willmann.
2Q14. A New Approach to Tandem Mirror Coil Design. D. A. D'Ippolito, G. L. Francis, and J. R. Myra.
2Q15. Interchange Stability of a Plasma in the Presence of Coherent, High Frequency Oscillations. J. R. Myra and D. A. D'Ippolito.

2Q16. Transport of Energy, Angular Momentum and Impurities in Neutral Beam Heated Tokamaks. F. L. Hinton and S. K. Wong.
2Q17. Magnetic Coordinate Representation of Stochastic Magnetic Fields. A. H. Boozer.
2Q18. Statistical Properties of Drift Wave Turbulence. W. Horton and P. Terry.
2Q19. Transport Instabilities in Tandem Mirrors and the Gunn Effect. S. P. Auerbach.
2Q20. Resistive Ballooning Mode Studies. T. C. Hender, B. A. Carreras, L. A. Charlton, J. A. Holmes, P. H. Diamond, and P. L. Similon.
2Q21. Criterion for Baldwin Instability in a Symmetric Tandem Mirror with Hot Electron End Plugs. X. S. Lee, K. T. Tsang, and B. Hafizi.
2Q22. Concepts in Waves. S. M. Omohundro and A. N. Kaufman.
2Q23. Monte Carlo Calculation of the Neoclassical Pinch Effect. J. W. Johnson, L. M. Lidsky, K. Hizanidis, and K. Molvig.
2Q24. Relativistic Evolution of Electromagnetic Instabilities. A. Ram and A. Bers.
2Q25. MHD and Rotational Stability of a Quadrupole Tandem Mirror. M. W. Phillips and J. D. Callen.
2Q26. Polarized Fusion Reactions. G. M. Hale and D. C. Dodder.

12:15 - 2:00 LUNCH

2:00 - 3:15 ORAL SESSION 2D

2D1. The Dynamo Effect in Long Time Reversed-Field Pinch Discharges. E. J. Caramana, D. A. Baker, and R. W. Moses.
2D2. Numerical Axial Stability Analysis for a Hot Electron Plasma in a Magnetic Trap. K. T. Tsang, B. Hafizi, and X. S. Lee.
2D3. Tokamak Disruptions. J. A. Wesson, A. Sykes, and M. Turner.

3:45 - 5:00 ORAL SESSION 2E

2E1. Mode Induced Beam Particle Loss in Tokamaks. R. B. White, R. J. Goldston, K. McGuire, A. H. Boozer, D. A. Monticello, and W. Park.
2E2. Elmo Bumpy Square. L. W. Owen and D. K. Lee.
2E3. Self-Consistent Calculation of Radial Transport in Tandem Mirrors. J. M. Gilmore, S. P. Auerbach, R. H. Cohen, A. A. Mirin, L. D. Pearlstein, and M. E. Rensink.

2:00 - 3:45 POSTER SESSION 2R

2R1. Transport of Rotating Tokamak Plasmas from Guiding Center Equations. S. K. Wong and F. L. Hinton.
2R2. Creation of High Energy Electron Tails Due to the Modified Two-Stream Instability. M. Tanaka and K. Papadopoulos.
2R3. High-m Tearing Mode Magnetic Turbulence. R. R. Dominguez and R. E. Waltz.
2R4. Transport Analysis in Small Stellarators. G. Kuo-Petravic and A. H. Boozer.

2R5. A Radiated Power Interpretation of the Murakami Limit. R. A. Hulse, F. W. Perkins, and D. E. Post.
2R6. An FRC Formation Method That Does Not Rely on Magnetic Field Line Tearing. R. D. Milroy.
2R7. Neutral Beam Driven Impurity Flow Reversal in TFTR and FED/INTOR. R. B. Bennett and W. M. Stacey, Jr..
2R8. Spectrum of Low Frequency, Non-Axisymmetric Oscillations in a Cold, Current-Carrying Plasma Column. K. Appert, J. Vaclavik, and L. Villard.
2R9. Poloidal Field Coil Design and Ideal MHD Stability of Bean-Shaped Plasmas. S. L. Mendelsohn, A. M. M. Todd, M. Okabayashi, M. S. Chance, and M. Reusch.
2R10. Ideal MHD Stability of Bean-Shaped Tokamaks. J. Manickam, M. S. Chance, and R. C. Grimm.
2R11. Delta Ray Production and Stability of Beam Propagation in Heavy Ion Beam Fusion. K. A. Brueckner and V. Stefan.
2R12. Kinetic Theory of Alfven Waves. S. M. Mahajan and J. E. Sedlak.
2R13. "Omitron" An Ohmic-Ignition Tokamak Experiment. A. Sestero.
2R14. Modular Coil Design and Magnetic Surfaces in Heliac. A. I. Shestakov, A. A. Mirin, and N. J. O'Neill.
2R15. Competing Attractors in Bumpy Tori. A. Punjabi and G. Vahala.
2R16. Resonant Absorption at the Lower Hybrid Frequency. W. Grossmann and H. Weitzner.
2R17. Finite Beta Effects on Drift-Wave Eigenmodes in Toroidal Plasmas. T. S. Hahm and L. Chen.
2R18. Modified Cat-d Fuel Cycles With or Without Tritium Assistance. G. W. Shuy and G. M. Borgonovi.
2R19. Magnetic Field Effects on Ion-Electron Temperature Relaxation. J. Galambos and G. H. Miley.
2R20. Study of ECRH Profile Control on the Stability of Resistive Tearing Modes. M. Rosenberg, V. S. Chan, and J. K. Lee.
2R21. Hot Plasma Decoupling Condition in Bumpy Cylinder Geometry. D. A. Spong, H. L. Berk, and J. W. Van Dam.
2R22. Bounce Averaged Calculation of ICRF Induced Ion Slideaway/Fusion Reactivity Enhancement. M. G. McCoy, G. D. Kerbel, S. C. Chiu, and R. W. Harvey.
2R23. Hybrid Simulations of Field Reversed Systems. P. M. Lyster, R. N. Sudan, and A. Mankofsky.
2R24. Resistive Effects on the Shear Alfven Wave in Tokamaks. C. E. Kieras and J. A. Tataronis.
2R25. Construction of Coils for Three-Dimensional Vacuum Fields Such as Stellarators. S. Yoshikawa.

4:00 - 5:45 POSTER SESSION 2S

2S1. Calculation of the Mercier Criterion for Stellarators. O. Betancourt and P. Garabedian.
2S2. Ion Transport in EBT-S. M. A. Iskra, T. K. Samec, G. Guest, and T. Kammash.
2S3. Computations of Plasma Resistivity in the Presence of a Reversed-Field Pinch Dynamo. R. W. Moses, Jr., K. F. Schoenberg, and R. L. Hagenson.
2S4. Equilibrium Calculations with Stellarator Expansion Techniques. K. E. Weimer and J. L. Johnson.
2S5. Dependence of Axis Shift on the Pressure Profile in an $\ell=2$ and the Optimized WVII-AS Stellarators. F. Herrnegger.
2S6. Finite-Bandwidth Effects on Lower Hybrid Current Drive. V. K. Decyk, G. J. Morales, and J. M. Dawson.
2S7. Drift Wave Turbulence in Toroidal Geometry. R. E. Waltz and R. R. Dominguez.
2S8. Some Analytic Approximations to Fokker-Planck Mirror-Loss Constants. R. F. Post.
2S9. Simulation of Inertial and Beam Driven Effects on Impurities in ISX-B. E. C. Crume, R. C. Isler, and D. E. Arnurius.
2S10. Simulating Turbulent Convection. C. G. Schultz and R. N. Sudan.
2S11. Simulation of Mode Coupling Equations for Drift Waves in Axisymmetric Tokamaks. L. Chen, C. Z. Cheng, and F. W. Perkins.

2S12. Particle Confinement Scaling in a Field-Reversed Configuration. L. C. Steinhauer.
2S13. EBT Plasma Performance with Improved Refueling Model. W. B. Downum.
2S14. Equilibria with Singular Currents in Tokamaks. M. S. Chu and T. H. Jensen.
2S15. Stability Studies Using the Stellarator Expansion. J. L. Johnson, G. Rewoldt, and M. S. Chance.
2S16. Cross-Field Free Electron Laser. R. C. Davidson, W. A. McMullin, and K. T. Tsang.
2S17. Runaways and Current Drive. L. Muschietti, K. Appert, A. H. Kritz, and J. Vaclavik.
2S18. Role of 2nd Harmonic ( ) ECRH in Maintaining a Tandem Mirror Thermal Barrier. T. D. Rognlien, R. H. Cohen, Y. Matsuda, and D. P. Grubb.
2S19. Equilibrium and Stability Properties of "Bean" Shaped Plasmas. L. A. Charlton, B. A. Carreras, T. C. Hender, J. A. Holmes, and B. F. Masden.
2S20. Monte Carlo Study of ECRH in Tokamak Plasmas. J. Y. Hsu and R. W. Harvey.
2S21. Integral Equation Solution to Magnetic Compressional Mode. M. Engquist and H. L. Berk.
2S22. Axisymmetric MHD Equilibria with Flow. W. Kerner and O. Jandl.
2S23. Analytical Investigations of Effects of Resistive Interchange Turbulence on Energy Confinement in Reversed-Field Pinch. Z. G. An and P. H. Diamond.
2S24. Adiabatic Compression and Translation of the S-1 Spheromak Plasma. H. Fleischmann, S. C. Jardin, Y. Sun, and M. Yamada.
2S25. A Possible Mechanism for Mass Flow Generation in Reversed-Field Pinches. J. P. Mondt and D. W. Hewett.

## WEDNESDAY MARCH 23

### 8:30 - 9:45 ORAL SESSION 3A

3A1. Suppression of the m=2 Rotational Instability in the Field-Reversed Configuration. D. S. Harned and D. W. Hewett.
3A2. Plasma Edge Turbulence. A. Hasegawa and M. Wakatani.
3A3. Steepest Descent Moment Method for Three-Dimensional MHD Equilibria. S. P. Hirshman and J. C. Whitson.

### 10:30 - 12:15 ORAL SESSION 3B

3B1. Theory of H-Mode Discharges in Diverted Tokamaks. T. Ohkawa, M. S. Chu, F. L. Hinton, H. Ikezi, Y. C. Lee, and C. S. Liu.
3B2. Scale-Variant Fractals and Plasma Collisions: The Truth About Classical Transport. S. Johnston.
3B3. Nonlinear Reduced Fluid Equations for Toroidal Plasmas. T. M. Antonsen, Jr. and J. F. Drake.
3B4. Universal Ideal-MHD Beta Scaling Law. L. C. Bernard, F. J. Helton, and T. N. Todd.

## 8:30 - 10:15 POSTER SESSION 3P

3P1. Comparison of EBT Experimental Results with a Neoclassical Model of Electron Transport. J. B. McBride, H. H. Klein, and N. A. Krall.

3P2. EBT Ring Creation and Control by Frequency-Modulated Microwaves. S. Hamasaki, N. A. Krall, and J. L. Sperling.

3P3. Parametric Generation of Electron and Ion Rings in EBT. V. Stefan and N. A. Krall.

3P4. Anomalous Absorption at Electron and Ion Cyclotron Harmonics in Elmo Bumpy Torus. N. A. Krall and V. Stefan.

3P5. Prospects for Achieving Ignition in High-Field Tokamaks. C. E. Wagner, R. A. Jacobsen, and R. E. Covert.

3P6. Loss Cone Instabilities in the TARA Anchor Cell. M. J. Gerver.

3P7. Electron Orbits in a Free Electron Laser with a Longitudinal Magnetic Wiggler. R. E. Aamodt.

3P8. Towards a Vectorized Monte-Carlo Beam Orbit Code in MHD Equilibrium Geometry, with Kitchen Physics. R. R. McCann, R. J. Goldston, and D. C. Mc Cune.

3P9. A Model for Electron Currents Near a Field Null. R. Stark and G. H. Miley.

3P10. An Evaluation of Second Harmonic Electron Cyclotron Emission as an Electron Temperature Diagnostic for the TMX End Cell. C. M. Celata.

3P11. Tilting Instability of Finite Aspect Ratio Ion Rings. C. B. Ruchti and R. V. Lovelace.

3P12. Particle Motion in the Field of a Modulated Wave. C. R. Menyuk.

3P13. Lower Hybrid Heating in the Ignitor Device. P. T. Bonoli, L. Sugiyama, and R. C. Englade.

3P14. Influence of Trapped Particles and Collisions on MHD Ballooning Modes. W. M. Tang, G. Rewoldt, and C. Z. Cheng.

3P15. Electromagnetic Turbulence and Dissipative Pressure-Driven Modes. P. H. Diamond, B. A. Carreras, and T. Hender.

3P16. Novel Method for Solving Stochastic Equations in Frequency Space. P. L. Andrews and R. E. Waltz.

3P17. Thermal Instabilities in the Edge Region of Reversed-Field Pinches. J. Goedert and J. P. Mondt.

3P18. Quasistatics of Two-Dimensional Plasmas. Z. Yoshida.

3P19. Studies of Current Generation by High Frequency Waves in Toroidal Geometry. B. Hui, K. R. Chu, and T. M. Antonsen, Jr..

3P20. Stabilization of the Tearing Mode at Low Densities by Turbulent Electron Diffusion. E. Esarey, J. P. Freidberg, K. Molvig, C. O. Beasley, Jr., and W. I. Van Rij.

3P21. A Phenomenological Theory of Nonlinear Saturation of Drift Wave Type Instability. A. K. Sen.

3P22. Bounce-Averaged ICRH for Toroidal Devices. G. D. Kerbel and M. G. McCoy.

3P23. Numerical Calculation of Axisymmetric Compact Torus Equilibrium Using Finite Elements. D. E. Shumaker.

3P24. Simulation of the Free Boundary Equilibria and Stability of Torus II Plasmas. A. A. Grossman, K. M. Ling, D. A. Monticello, and J. Manickam.

3P25. Calculation of the Lyapunov Spectrum. J. M. Greene, Y. F. Chang, and J. Wright.

## 10:30 - 12:15 POSTER SESSION 3Q

3Q1. Ion Heating and Acceleration by Strong Magnetosonic Waves. B. Lembege, S. T. Ratliff, J. M. Dawson, and Y. Ohsawa.

3Q2. A Reappraisal of Neoclassical Ion Heat Conduction in Tokamaks. A. A. Ware.
3Q3. Variational Method for Three-Dimensional Toroidal Equilibria. A. Bhattacharjee and J. C. Wiley.
3Q4. Nonlinear Evolution of Tearing Modes. Y. Pao and S. Z. Zhao.
3Q5. Computer Simulation of ECRH in an Inhomogeneous Magnetic Field. A. T. Lin and C. C. Lin.
3Q6. Mode Conversion and Electron Heating Near the Upper Hybrid Resonance Frequency. H. Okuda and B. Smith.
3Q7. Monte Carlo Studies of Central Cell ICRF Heating and RF Start-Up in TARA, and RF Fueling in MARS. A. M. M. Todd.
3Q8. Sawtooth Oscillations, Magnetic Disturbances, and Toroidal Flux Regeneration in the ZT-40 Reversed-Field Pinch. R. G. Watt and R. A. Nebel.
3Q9. A Theoretical Study of Axial Confinement in Tandem Mirrors. R. B. Campbell.
3Q10. Ballooning Modes in Axisymmetric Tandems. R. P. Freis, B. I. Cohen, and W. A. Newcomb.
3Q11. Necessary Number of Modes, Multiplicity of Asymptotic States, and Hysteresis in Rayleigh-Benard Convection. Y. M. Treve.
3Q12. Moderate-M Ballooning Modes in Tandem Mirrors. W. M. Nevins and L. D. Pearlstein.
3Q13. The Modelling of a Long, Thin Mirror Machine. H. Weitzner and H. Strauss.
3Q14. Exact Nonlinear Solutions to the Reduced MHD Equations and High Frequency MHD Activity. P. J. Morrison and R. D. Hazeltine.
3Q15. Variational Theory of Current Drive. D. A. Hitchcock and S. M. Mahajan.
3Q16. Numerical Study of Thermal Equilibria and the Catastrophe Model for Major Disruption in Tokamak. G. Y. Yu, P. N. Guzdar, and Y. C. Lee.
3Q17. Anomalous Transverse Diffusion of Electrons in a Uniform Magnetic Field. K. Matsuda.
3Q18. Electron Cyclotron Radiation from Two Interpenetrating Plasmas in TMX-Upgrade. T. V. Leid and C. M. Celata.
3Q19. Mode Coupling Near Cyclotron Resonance in a Weakly Relativistic and Inhomogeneous Electron Plasma. K. Imre and H. Weitzner.
3Q20. RF-Induced Spatial and Velocity-Space Diffusion in Cylindrically-Symmetric Mirrors. B. Hafizi and R. E. Aamodt.
3Q21. Spectrum of Dissipative Drift Wave Turbulence in Tokamaks. P. W. Terry and P. H. Diamond.
3Q22. A Numerical Analysis of the EBT Flute Modes in the Low Poloidal Mode Number Limit. A. M. El Nadi, D. A. Spong, and J. C. Whitson.
3Q23. A Resonant Cavity ICRF Coupler for Large Tokamaks. F. W. Perkins and R. F. Kluge.
3Q24. On the Cutoff Density of Current Drive by LH Waves. E. Canobbio and R. Croci.
3Q25. Effects of the Hall Term on the Resistive Interchange Instability in Spheromak. J. DeLucia and S. C. Jardin.

# EQUILIBRIUM AND STABILITY PROPERTIES OF HIGH BETA TORSATRONS*

B. A. Carreras, W. A. Cooper, L. Garcia, T. C. Hender
H. C. Hicks, J. A. Holmes, and V. E. Lynch
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Equilibrium and stability properties of high β torsatrons have been investigated by numerical and semi-analytical techniques. Three numerical approaches have been used to study plasma equilibria for different coil configurations. The method of averaging[1,2] permits fast equilibrium and stability calculations, and therefore is used to scan large regions of parameter space. Two full 3-D codes, namely the Chodura-Schlüter code,[3] and the NEAR code[4] recently developed at ORNL, are used to explore selected regions of parameter space. The resulting equilibria calculated with different methods are in good agreement. This validates the average method approach and enhances its usefulness.

We have studied configurations with different aspect ratios and numbers of field periods. The role of the vertical field has also been studied in detail. The main conclusion is that for moderate aspect ratio torsatrons ($A_p \lesssim 8$), the self-stabilizing effect of the magnetic axis shift is large enough to open a direct path to the second stability regime.

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

[1] J. M. Greene and J. L. Johnson, Phys. Fluids, 4, 875 (1961).
[2] L. M. Kovrizhnykh and S. V. Shchepetov, Sov. J. Plasma Physics 6, 553 (1980).
[3] R. Chodura and A. Schlüter, J. Comput. Phys. 41, 68 (1981).
[4] T. C. Hender et al., Numerical Simulation Conference, San Diego, 1983.

# FORMATION OF ENERGETIC TAIL ION SPECIES DURING THE NEGATIVE POTENTIAL OPERATION IN EBT

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ABSTRACT

The physical mechanism for the hot ion species formation during the quiescent T-mode operation in EBT devices has been a major mystery in understanding the EBT physics. We have identified a classical mechanism leading to the conclusion that the existence of the hot ion species during the T-mode operation is a natural phenomenon indebted to the particularity of the geometry and equilibrium. During the T-mode regime of operation, the negative potential well, whose depth is much greater than the background ion species thermal energy, is formed. As a result, the ions experience rapid inward (radially) diffusion, falling down the electrostatic potential hill and acquiring kinetic energy. Such a heating process (electrostatic heating) is found to be rapid enough to generate a non-Maxwellian ion tail species to the experimentally observed level. A corresponding theoretical model for the transition into the unstable M-mode will also be presented.

# DRIFT-ALFVEN MODES IN HIGH CURRENT PINCHES

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Field-aligned current couples the decelerated and accelerated drift-Alfven modes together. When the coupling is strong enough, instability results. The behavior of drift-Alfven modes in high current pinches is investigated in realistic geometries using ballooning formalism. In flux surface coordinates the coupling term is proportional to f" (the second derivative of current flux with respect to magnetic flux) and is insensitive to the details of the current-carrying velocity distribution functions. It is conjectured that this type of instability is responsible for the relaxation toward the Taylor's state in which f" = 0. In the high electron parallel conductivity limit, the real part of the frequency is $\omega^*_{ip}/2$ (half of the ion diamagnetic frequency), which is consistent with experimental observations on the OHTE device. Structures of the solutions of the along-the-field-line equation vary from damped oscillatory to monotonically decreasing as the strength of magnetic shear increases with respect to the coupling term.

This work is in part supported by Phillips Petroleum Company and GA Technologies Inc. under a joint research and development agreement (GA Reference No. 01341).

# CONFINING POTENTIAL IN A THERMAL-BARRIER TANDEM MIRROR WITH STRONG ECRH IN THE PLUGS*

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The application of strong electron-cyclotron resonance heating (ECRH) to plug electrons in a tandem-mirror thermal-barrier cell can strongly affect the potential difference $\Phi_{pb}$ between the plug and barrier regions. This problem is considered here using model distribution functions which are Maxwellian in the portion of velocity space corresponding to electrons which pass into the central cell, and constant along r.f. heating characteristics elsewhere in velocity space. Two models are considered. The ECRH is assumed to be (nonrelativistically) resonant at the plug potential peak in the first model, and at both the plug and barrier in the second. Comparison with results from a multi-region, bounce-averaged Fokker-Planck code shows that the models are surprisingly good for the ECRH amplitudes and machine parameters contemplated for MFTF-B and TMX-U. The model distribution functions are integrated to obtain analytic expressions for the electrostatically-trapped or total density vs. potential and magnetic field strength. These expressions imply power-law relationships between the potential and the plug-to-barrier density ratios. These relationships are considerably more favorable for tandem mirror confinement than the modified Boltzmann law[1] (logarithmic relationship) appropriate for collisional plugs. Estimates of the ECRH power required to sustain the distribution functions are also given.

[1]R.H. Cohen, I.B. Bernstein, J.J. Dorning and G. Rowlands, Nucl. Fusion 20, 1421 (1980).

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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.

# TURBULENT RELAXATION OF COMPRESSIBLE PLASMAS WITH FLOW*

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Relaxation of compressible plasmas to an equilibrium state with flows has been studied. The MHD equations with the added assumption of large parallel thermal conductivity and ergodic magnetic field lines show that $\int \underline{v}\cdot\underline{B}$ is an invariant even when plasma compression is included. Also, $\int \rho \, \ell n(p/\rho^{\gamma})$ is the only entropy-like invariant of the MHD equations with large parallel thermal conductivity. The other invariants of the motion are energy, magnetic helicity $\int \underline{A}\cdot\underline{B}$, mass $\int \rho$, and angular momentum (if the container is axisymmetric.) Equilibria are found by extremizing energy while conserving these invariants. These invariants are shown to be complete in the sense of generating all equilibria that form after relaxation with ergodic field lines. For parallel flows, two classes of solutions are obtained, characterized by the sign of $d\rho/dB^2$. A sufficient condition for stability is derived. This condition is never satisfied by the class of equilibria with $d\rho/dB^2 > 0$, indicating the possibility of unstable resistive interchanges. The class of equilibria with $d\rho/dB^2 < 0$ is stable if generalizations of the local firehose and mirror criteria are satisfied and if the generalized Taylor helicity eigenvalues[1] exceed those of the equilibrium. A comparison of these conditions with those of Frieman and Rotenberg[2] is discussed.

1. J. B. Taylor, Phys. Rev. Lett. 33, 1139 (1974).
2. E. Frieman and M. Rotenberg, Rev. Mod. Phys. 32, 898 (1960).

* Supported by U.S. Department of Energy.

# COLLISIONLESS DRIFT AND TEARING MODES IN A PLASMA CYLINDER WITH MAGNETIC SHEAR*

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Collisionless drift and tearing modes have been studied exhaustively in slab geometry and moderately in toroidal geometry. In slab geometry drift modes are found to be stable. In tokamak geometry drift waves are driven unstable by trapped particles and mode coupling, in spite of the average good curvature. The present analysis seeks to determine the stability of these modes in cylindrical geometry, in which mode coupling and trapped particles are absent, but the curvature is bad. We note that this geometry closely models large-aspect-ratio systems such as the reversed-field pinch.

As part of this study we have derived equations that describe both drift and tearing modes. In order to treat the curvature effects consistently, we include all of the $\theta(\beta)$ convections due to curvature drifts, magnetic gradient drifts, and parallel field perturbations. In the limit of zero ion temperature, it is possible to prove that there exist no unstable local kinetic modes unless the Suydam criterion, $D_s < 1/4$, is violated. This result is surprising when contrasted with resistive MHD theory, which predicts localized "resistive-g modes" when $0 < D_s < 1/4$.

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* Work supported by the U.S. Department of Energy under contract no. DE-FG05-80ET-53088.

# THREE-DIMENSIONAL MHD EQUILIBRIA OBTAINED USING THE INVERSE SPECTRAL (MOMENT) METHOD*

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The numerical methods used to solve the MHD equilibrium equations in the inverse (moment) representation are presented. The MHD variational principle (discussed in an accompanying paper) is used numerically in three respects: (1) as a means for truncating the Fourier flux coordinate representation of $\vec{X}$ in the most convergent manner; (2) to determine the equilibrium equations in a conservative form suitable both for finite differencing and for applying fixed, as well as free, boundary conditions; and (3) to obtain an algorithm for finding the path of steepest energy descent in the phase space comprised of the Fourier moment amplitudes. The Fourier analysis in the poloidal and toroidal angles reduces the equilibrium equations to one dimensional second order ordinary differential equations which, with the addition of first and second order time derivatives, become a critically damped hyperbolic system. Several time-stepping algorithms are discussed, including a stiff-integration scheme (neglecting second order time derivatives) and an explicit predictor-corrector (Adams) method. Although the magnetic axis is a singular point of the flux coordinate system, it can be handled without difficulty by power series expansion of all equilibrium quantities in its vicinity. The critical importance of the renormalized poloidal angle $\theta$ is explored by considering exact two-dimensional inverse solutions of the Solove'ev type. Finally, examples of two-dimensional "kidney" shaped equilibria, as well as a three-dimensional corrugated tokamak equilibria, are presented.

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

# Computation of Field-Reversed θ-Pinch Equilibria

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New York University

## ABSTRACT

We compute field-reversed θ-pinch equilibria with and without mass flow using the 1 1/2D algorithm of Grad[1]. Interchange stability implies a very large current density near the separatrix due to the singularity at the X-points. In the usual calculations this current peak is overlooked. We find that this deficiency gives rise to a jump in $p+B^2/2$ across the separatrix, that is, there is no force balance between the plasma and the vacuum regions. We correct the calculation by determining the total current deficit near the separatrix and analytically determining its distribution, which is then deposited accordingly. The equilibria obtained are more elongated and football shaped rather than racetrack.

The results are compared with an equilibrium having the same "adiabatic" parameters in the bulk of the plasma except near the separatrix where no high current peak is expected (but which is interchange unstable). The two equilibria are almost identical in the bulk of the plasma and differs only near the separatrix, suggesting the accuracy of our code over the physically relevant plasma domain.

1. H. Grad, Courant Institute Report MF-93, October 1978.

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76ER03077.

# Particle Simulation Study of Drift Wave Turbulence

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Three dimensional electrostatic particle simulations, using a multi-surface sheared slab model, have been carried out to investigate the nonlinear physics of drift waves. The particle code used is a 3-D normal mode expansion (z-direction) method[1] with guiding center electron and full dynamic ions. All ion Landau resonances are made to lie within the system so that a correct eigenmode structure is established and many electron resonant surfaces are packed in order to incorporate nonlinear electron effects. System sizes of $L_x \times L_y \times L_z$ = $64 \times 64 \times 6400$ with $\phi(0)=0=\phi(L_x)$ or $\phi'(0)=0=\phi'(L_x)$ boundary conditions in the x-direction were used. Typical parameters are $m_e/m_i=.01$, $T_e/T_i=1$, $\kappa \equiv 1/L_n=.07$, $L_s/L_n=28$, $n_o=16$ particles/cell, $\rho_i=2.5\Delta$, $\omega_{ce}/\omega_{pe}=10$, $\omega_{pe}\Delta t=3$-$4$, $v_{the}=2.5\omega_{pe}\Delta$, $a_x=a_y=1.5\Delta$, $A_z=320\Delta$. Modes with $1 \leq q(\simeq m/n) \leq 2$ were retained in the simulations.

Properties of drift waves depend upon rational surface separation $\Delta x_{mn}$ and initial fluctuation levels. The numerical simulations reveal that when the resonant island width of a drift mode $w_{mn}$ is less than the separtion $\Delta x_{mn}(S=w_{mn}/\Delta x_{mn}<1)$, stable drift eigenmodes occur.

Preliminary results show that when the Chirikov overlap condition, $S>1$, is satisfied, unstable modes are observed $(0.5 \leq k_y\rho_i \leq 1)$ with saturation levels of $e\phi/T_e \leq 10^{-2}$ (50% above noise level). The ratio of the electron decorrelation frequency $\omega_c$ to the wave frequency $\omega$ was $\omega_c/\omega \lesssim 1$. The drift wave spectrum shows mode localization about $x_{mn}$ (position of rational surface) and amplitude decay beyond $x_i$ (ion Landau resonance point). Measured frequencies show agreement with those obtained from a shooting code.

1. C. Z. Cheng, H. Okuda, J. Comp. Phys. 25, 133 (1977).

This work was supported by DOE and NSF and carried out in collaboration with M. N. Rosenbluth.

# Particle Simulation of Drift Instabilities

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Two-and-one-half dimensional electrostatic particle codes with guiding center electron and full dynamic ions[1] are used to study density gradient driven drift instabilities in a bounded sheared slab with a single rational surface. Typical parameters are: number of particles per cell = 16, $\lambda_e = 2.5\Delta$ ($\Delta$=unit grid spacing), system size $L_x \times L_y = 64\Delta \times 32\Delta$, $M_i/m_e=100$, $T_e=T_i$, $\rho_i=2.5\Delta$, $\kappa=L_n^{-1}=0.07$, $L_s/L_n= 14, 28$. The system is bounded in the x direction with either $\phi=0$ or $\phi'=0$ boundary conditions.

In order to study the eigenmode structure, the ion Landau resonance layer is contained within the system. In order to accomodate the correct parity of drift wave eigenmodes, the rational surface at $x_s$ is moved away from the $\phi=0$ boundary or $\phi'=0$ is employed. Stable eigenmodes whose structure is close to shooting code predictions seem to prevail. Cases with $L_s/L_n=28$ and $L_s/L_n=14$ show no appreciable difference for stability. A case with $L_s/L_n=56$ where convective amplification may be important is under study.

1. W. W. Lee and H. Okuda, J. Comp. Phys. 26, 139 (1978).

This work supported by DOE Grant DE-FG05-80ET-53088 and NSF Grant ATM82-14730, and was carried out in collaboration with P. H. Diamond and M. N. Rosenbluth.

POSTER SESSION: adjacent to "Particle Simulation Study of Drift Wave Turbulence" by Sydora et al.

# SHARP BOUNDARY EQUILIBRIA IN TANDEM MIRRORS*

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Previous work on MHD stability including FLR indicates that only the rigid displacement limits the attainable betas in tandem mirrors in the ideal MHD limit. These analyses used quadrupole equilibrium obtained by expansion through first order in beta in the paraxial limit. In this work we extend this analysis to all orders in beta by limiting ourselves to pressure profiles which are step functions in flux. The procedure produces a non-linear, second order ODE along the field lines which is obtained by satisfying the appropriate jump conditions at the plasma surface. The basic assumption made is that the surface is approximately elliptical with the shape obtained by minimizing the first order energy. A new result obtained for the "double fan" configuration of MFTF-B is that the eccentricity ($\varepsilon$) in the central cell satisfies

$$\varepsilon = \frac{\Sigma^{-}L + \Sigma^{+}\Lambda L}{1 + \Sigma^{+}L}$$

where L is the central cell length, $\Sigma^{+(-)}$ is the integral over the normal (geodesic) curvature and $\Lambda$ is essentially the integral of the geodesic curvature over one fan. We see that even when $\Sigma^{-} = 0$ (a design criteria), there is still elliptical distortion if $\Sigma^{+}L \geq 1$.

*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.

# DYNAMO ACTION FROM STABLE ALFVÉN WAVES*

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Using a variational formulation, stable Alfvén waves have been found that can effectively oppose the diffusion of a Reversed-Field Pinch profile towards an unstable state. Linear eigenfunction calculations and resulting diffusion calculations will be presented.

*Work performed under the auspices of the USDOE

UCRL ABSTRACT
88692

# 3D CALCULATIONS OF SELF-CONSISTENT ELECTROSTATIC AND MAGNETOSTATIC EQUILIBRIA IN TANDEM MIRRORS*

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The distinguishing feature of tandem mirror confinement schemes is the ambipolar electrostatic trapping of the central cell ions. As a result the equilibrium configuration depends strongly on the electrostatic as well as on the magnetostatic fields. Our model, as embodied in the VEPEC computer code, solves the guiding center fluid equilibrium problem assuming the drift orbits are omnigenous. Several plasma components, including electrons, are treated on a multiregion domain. The $\ell$th component's pressure function is assumed to have a factored form: $P_\ell(B,\phi,\psi) = w(\psi)\hat{P}_\ell(B)F_\ell(\phi)$. Then the assumption of quasi-neutrality determines $\phi = \phi(B)$ in each axial region. We use a vector potential representation and solve the non-linear Ampere's law equation by finite element techniques. While our code has been designed to compute very complicated configurations such as MFTF-B, we are presently testing it on the relatively simpler original TMX device where comparisons may be made with existing experimental results.

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

# STOCHASTIC ELECTRON HEATING DUE TO ICRH IN EBT-S*

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In the EBT geometry, the annular electrons are classified into trapped and passing particles. Motion near the boundary between trapped and passing orbits is studied both numerically and theoretically for the appropriate parameters of ICRH experiments on EBT-S. Stochastic electron motion is observed within these experimental parameters range resulting in wave power being transferred to the electrons by stochastic diffusion. The temperature increase of the electron annuli found on the recent ICRH experiments on EBT-S[1] could be explained from this heating mechanism. The detail of calculation and comparison with experimental result will be discussed.

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

[1] T. L. Owens, et al., "Heating Experiments in the Ion Cyclotron Range of Frequencies on EBT-S," (to be published in Nucl. Fusion 23, No. 1, 1983).

# FOKKER-PLANCK INVESTIGATIONS OF RF CURRENT DRIVE*

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M.I.T.

Two-dimensional Fokker-Planck studies of rf current drive are now being approached from a different perspective. Rather than the careful and often tedious Fokker-Planck simulation of this problem using an initial value approach, we are now investigating the possibility of solving only for the time asymptotic state. Solution time can be decreased by an order of magnitude by relaxing the requirement of correctly following the time history of the evolution. The increased speed of the calculation allows a much greater parameter regime to be included in our studies. We intend to investigate the required rf amplitudes needed to drive currents comparable with benchmark cases with electric fields.

*Work supported by the U.S. Department of Energy under Contract No. DE-AC02-78ET-51013.

# A THEORY OF THE RELAXATION OF TOKAMAK DISCHARGES*

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A model of Tokamak equilibria as minimum energy states[1] is presented. Assuming a current penetration phase occurring over periods short compared to pinching via broad-band, saturated E-M turbulence, a "Sonic Bath"[2] relaxation model is applied. A thermal saturation scaling of the turbulence and excess energy absorption into unconfined plasma are assumed. Considering the relaxation as a linear transformation, it is shown that flux invariants must be quadratic for this model. Two quadratic invariants, A·B and poloidal flux squared, are shown to exist and give a modified Maschke[3] model equilibrium with $P \alpha \psi^2$ and $rB_\theta \alpha(\psi + B_o)$. In contrast to Maschke's equation, the vacuum toroidal B field introduces an inhomogenous term. This term is found to give "shoulders" on the current profile at $\beta_p < 1$ and to give edge current reversal for $\beta_p > 1$. The recently observed appearance of reversed currents in the high beta tokamak TERP-II[4] and their suspected appearance in the TORUS-II[5] is thus explained. Good agreement between theoretical and experimental pressure profiles is found for low $q\ell$ discharges. A "Main Sequence" relationship of current profile broadness to $\beta_p$: $q\ell/q_o \cong 1.17(1+\beta_p)$, is found for circular discharges and agrees well with low $q\ell$ discharge data as a limiting law.

*Work supported by the U.S. Department of Energy under Contract DE-AC04-76-DP00789.

1 J. B. Taylor, Phys. Rev. Lett. 33, 1139 (1974).
2 J. E. Brandenburg, APS Bull. 26, 905 (1981).
3 E. K. Maschke, Plasma Physics 15, 535 (1973).
4 J. A. Antoniades, G. C. Goldenbaum, B. V. Weber, A.P.S. Bull. 27, 973 (1982).
5 A. Navartil and F. M. Levinton, A.P.S. Bull. 27, 973 (1982).

# Shear Alfvén Waves in Tokamaks*

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Ideal and resistive MHD equations for the shear Alfvén waves are studied in a low-$\beta$ toroidal model. The ion sound effects are neglected. For an infinite shear slab, the ideal MHD model gives rise to a continuous spectrum of real frequencies and discrete eigenmodes (Alfvén-Landau modes) with complex frequencies. With toroidal coupling effects, the continuum is broken up into small segments of continuous spectra. In addition, unstable ballooning eigenmodes are introduced by the bad curvature when $\beta > \beta_c$. The Alfvén-Landau modes are insensitive to the toroidal coupling effects. Including resistivity ($\eta$), four branches of eigenmodes exist in the resistive MHD model: (1) Shear Alfvén-Landau modes which are insensitive to resistivity as well as toroidicity, (2) Periodic shear Alfvén waves which approach to the end points of the continuous spectra as $\eta^{1/2}$ when $\eta \to 0$, (3) Resistive entropy modes which are stable with frequencies going to zero with resistivity as $\eta^{1/3}\exp(-i\pi/6)$ and $\eta^{1/3}\exp(-i5\pi/6)$, (4) Resistive ballooning modes which are purely growing with growth rate proportional to $\eta^{1/3}$ as $\eta \to 0$ for $\beta > 0$.

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

# ANALYTIC RESISTIVE SHEAR ALFVÉN WAVE SPECTRUM IN A CYLINDER*

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Analytic solutions for the resistive shear Alfvén wave spectrum in a simple zero beta tokamak-like equilibrium in a cylinder will be presented.

It will be shown that the spectrum remains complex in the limit $\eta \to 0$.

Connections with the ideal spectrum and implications for Alfvén resonance heating will be discussed if time permits.

*Work performed under the auspices of the USDOE.

# Effect of the Ambipolar Potential on the Confinement of Reactor-Scale Stellarators*

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The confinement properties of stellarators with reactor-like parameters are re-examined, in the presence of a self-consistent ambipolar potential $\Phi$, and in light of current theoretical expectations for the dependence of the transport coefficients D on collision frequency $\nu$ and radial electric field $E = -\Phi'$. In particular, the appropriate expressions for D at low $\nu/E$ are different[1,2] from those employed in earlier work.[3,4]

It is found that stellarators have sufficiently good confinement to be viable as reactors. In addition, it is found that multiple roots of the ambipolarity constraint can exist in stellarators (as in EBTs and possibly tandem mirrors), and that, for appropriate parameters, confinement can be improved by operating at a root different from the one usually considered. Explicit expressions are developed determining when multiple roots will exist, and whether improved confinement may be expected.

*Work supported by the U.S. DOE under contract number DE-AC02-78-ET 53082.

1. A.A. Galeev, R.Z. Sagdeev, Sov. Phys. Uspekhi 12, 810 (1969).
2. H.E. Mynick, Univ. of Wisconsin Report TSL-83-1 (1983).
3. A.A. Galeev, R.Z. Sagdeev, H.P. Furth, M.N. Rosenbluth, Phys. Rev. Lett. 22, 511 (1969).
4. R.M. Kulsrud, D. Ho, Proc. Sherwood Theory Meeting, paper (4:9) (1982).

# Kinetic Effects and Stabilization of Flute Instability in Sheared Magnetic Fields*

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Stability of inhomogeneous plasma in inhomogeneous magnetic field with shear is investigated using 2-1/2 dimensional bounded electrostatic code (an extension of the work of Goede and Humanic[1]) on the CHI computer. The results are compared with theoretical prediction from fluid and kinetic theory.

The inhomogeneities in density and B are given by $n(x) \propto \frac{1}{(R_o+x)^N}$ and $B_z(x) \propto \frac{1}{(R_o+x)}$ ; there is a small constant $B_y$ so the combined field has shear. Energy principal consideration predicted that for $B_y = 0$, the plasma is stable when $N < 2$ and unstable otherwise; simulation showed instability for $N > 1.1$. We investigate stabilization by adding a small $B_y$. The plasma is stabilized with very small $B_y$ ($\frac{B_y}{B_z} \sim 0.02$). The stabilizing $B_y$ is derived theoretically and compared with simulation results. It is found that the agreement is within a factor of two or so. Many simulation runs are performed using different parameters (e.g. plasma density, temperature, mass ratio, magnetic field strength, and inhomogeneous scale length are varied) and the results are compared with theoretically predicted dependences. The observed dependence on temperature and inhomogeneous scale length compare well with theoretical growth rates; the other dependences are not well predicted by theory. Both theoretical and simulation results will be presented.

*Work supported by U.S.D.O.E. Contract No. DE-AM03-76SF00010 PA 26, Task VIB.

[1]H. Goede, D. Humanic, and J.M. Dawson, UCLA Report PPG-659 (1982).

# Resistive Axisymmetric Evolution of the Bean Tokamak*

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The bean shaped tokamak requires the presence of at least one nearby poloidal field coil to provide shaping control to form the bean cross section. We investigate the ideal and resistive MHD axisymmetric stability of such a configuration by using a modified version of a two-dimensional resistive MHD code[1] originally designed to study the formation of spheromaks.

The most dangerous instabilities are expected to be (1) a nearly vertical displacement caused by the unfavorable effective field index and (2) a doublet or droplet formation displacement in which the waist of the bean pinches off. We investigate the feasability of feedback control of these instabilities by solving coupled circuit equations for the poloidal field coils simultaneously with the plasma evolution equations.

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

[1]S. C. Jardin and W. Park, Phys. Fluids <u>24</u> (1981).

# COLLISIONLESS INTERNAL KINK MODES

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The stabilization of the ideal MHD internal kink mode in high beta regimes has recently been demonstrated.[1] However, nonideal effects play a role in the vicinity of the second point of marginal stability. Thus we consider a narrow layer centered on the mode resonant surface in which magnetic reconnection may occur, and adopt a full kinetic approach to deal with the collisionless limit in which the fluid description breaks down. The mode structure is described to all orders in the ion gyroradius by an integro-differential system of equations for the electrostatic and parallel magnetic potentials. From this we derive a convenient quadratic form suitable to obtain analytic estimates of the mode growth rate. Neglecting effects associated with temperature gradients we show that the collisionless mode is stable above a finite beta threshold. Stability in the presence of finite temperature gradients is also discussed.

*Work supported by the U.S.D.O.E.

[1] G.B. Crew and J.J. Ramos, Phys. Rev. A26, 1149 (1982).

# Comparison of MHD Equilibrium Calculations Using the Stellarator Expansion

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The recent revival of interest in stellarators has made it useful to develop reduced models which contain the essential physics. The best developed simplification utilizes the stellarator expansion[1], which is based on a large-aspect-ratio approximation and thus is quite realistic for many stellarator designs. In this model the lowest-order magnetic surfaces, which determine the MHD equilibrium properties, are determined from solvability conditions associated with equations obtained in the higher orders in the expansion. Although the equations which must be solved are axisymmetric and contain the helical field effects only through averaged quantities, the higher order effects are correctly included.

Different implementations of the resulting equations for MHD equilibrium have been made both at Princeton and at Oak Ridge. Corresponding results from the two codes have been compared.

In the original form of the stellarator expansion[1], toroidal effects appear only in second order in the expansion. The inclusion of some of these toroidal effects in the lowest order equations should make the stellarator expansion approach applicable to designs with smaller aspect ratios. Results of this extension for the two implementation will be compared.

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

#Work supported by U.S. DoE, under contract W-7405-eng-26 with the Union Carbide Corporation

1J. M. Greene and J. L. Johnson, Phys. Fluids 4, 875 (1961).

# The Impact of the Ring Electron Distribution on The Stability of EBT*

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Considerable variation in the stability results and associated core beta limits in EBT has emerged in recent years as a result of various approximations made concerning the velocity distribution function of the hot electrons. In this paper we assess the role of such a distribution by examining EBT stability in a "slab" model, where field curvature is simulated by a gravitational force, and in a "local" model in which curvature effects enter in a natural way. With the aid of a full dispersion equation, we find in the slab model that the interchange modes are sensitive to the distribution function while the compressional Alfven waves are not. In the local model we find that the interchange modes are insensitive so long as the anisotropy is large while other modes do reflect dependence on the distribution function. Finally we domonstrate that in the "deep well" case the results for both modes are independent of the model and of the distribution function.

*Work supported by DOE

# Coupling Theory of the JET ICRH Antenna

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The JET antenna has been conceived as a "Limiter Antenna", completely recessed in a lateral frame which has the dual purpose of protecting the conductors and limiting the plasma radius. The coupling of this antenna is calculated in a slab geometry, both analytically and numerically, using a variational formulation /1/ which finds the self-consistent currents in the antenna elements. Full account is taken of the modes excited inside the limiter frame and of their coupling to waves in an inhomogeneous plasma. Curves for the optimization of power coupled are obtained as functions of frequency and of transmission-line impedance. The electric and magnetic fields, their power flux inside the plasma and their dispersion are then found as a function of penetration. In particular, the JET antenna design supresses the excitation of surface waves which are suspected of contributing to impurity generation during RF heating /2/.

/1/ K. Theilhaber, J. Jacquinot,
EUR-CEA-FC-1166, November 1982.

/2/ Equipe TFR, Heating in Toroidal Plasmas, Proc. of the Third Joint Varenna-Grenoble International Symposium, March 1982, Grenoble, France, p. 225.

Drift Wave Turbulence and Shielding

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In toroidal geometry, the toroidicity-induced drift modes are driven unstable by trapped electrons. Ion Compton scattering redistributes energy among modes. We examine here the effect of shielding, i.e. the ion polarization terms in the Direct Interaction Approximation. It is shown that these terms, which involve the dielectric properties of the plasma, reduce indeed Compton scattering (as in local, weak turbulence theory), but do not change qualitatively the picture, because of finite Larmor radius effects. Even for low $\beta$ plasmas, when the modes are mostly electrostatic, the field line pertubations are sufficient to affect electron energy transport, that we evaluate. We compute also the amount of nonlinear ion heating. Finally we present a preliminary, nonperturbative approach to renormalization of the electron equation, including polarization terms.

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POSTER SESSION

*

# FAT BANANAS IN EBT*

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In an asymmetric device like the ELMO Bumpy Torus (EBT), the radial width of the collision orbits is not determined fully until the self-consistent ambipolar potential is known. There is a class of potentials for which the orbit width is not small compared with the equilibrium scale lengths, thus calling into question standard linear diffusion theory. A diffusion equation is derived in the constants of motion space for a hot minority species undergoing large orbits in a cold dense species. This equation is solved to all orders in the step-size parameter, and the solution is examined in various limits. In particular, it is found that only odd derivatives of the hot species bulk Maxwellian drive diffusion, making the corrections to linear diffusion theory to second order in the step-size parameter.

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

# EXTENSIONS OF THE ORNL EBT MONTE CARLO DIFFUSION CODE*

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The recently developed EBT Monte Carlo Resonant Diffusion code[1] has been extended to examine the effects of nonzero poloidal electric field and finite width crescent shaped orbits. Numerical results are compared with recent analytic results. Extensions to include pitch angle effects through bounce-averaging of the Monte Carlo collision operator will be presented. Using a bounce-averaged collision operator retains the advantage of a 2D code while including 3D effects. Inclusion of pitch angle scattering allows examination of non-resonant diffusion.

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

†Computer Sciences at Oak Ridge National Laboratory.

[1]J. S. Tolliver et al., "Monte Carlo Calculation of Resonant Diffusion Coefficients in EBT and the Applicability of Local Diffusion Theory," to be published in Physics of Fluids.

Please place with other EBT transport posters by E. F. Jaeger and by D. E. Hastings

# SENSITIVITY OF GLOBAL CONFINEMENT PROPERTIES IN EBT TO THE EXISTENCE OF AN AMBIPOLAR POTENTIAL WELL*

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Recent radial transport calculations for EBT-S suggest that global confinement properties are less sensitive to the existence of an ambipolar potential well than previously thought. We consider an ad hoc ambipolar potential profile in which the well depth can be varied continuously while maintaining a constant positive radial electric field at the plasma edge. Radial transport calculations with this potential show modest variation in global energy containment time as the potential well depth $\Delta\phi$ is varied from $\Delta\phi \sim 0$ to $\Delta\phi \sim kTe/e$.

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

# RAY TRACING ANALYSIS OF THE LOWER HYBRID EXPERIMENT ON THE WISCONSIN OCTUPOLE*

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Ion heating has been measured over a wide range of plasma parameters for sufficiently high values of density and magnetic field corresponding to the appearance of the hot plasma lower hybrid mode conversion layer in the University of Wisconsin octupole. Results have been explained by invoking an upshift in the $n_{||}$ wave spectrum emitted from the antenna.[2] Subsequent wave measurements on the octupole have provided supportive evidence for this hypothesis. In this paper we summarize the experimental results and present an interpretation of the data using a modified version of the ray tracing code, RAYS, developed at Oak Ridge National Laboratory.[3] This version of RAYS calculates wave propogation using the electromagnetic cold plasma dispersion relation with a magnetic field and density model appropriate for the octupole. Electron Landau damping and the possibility for conversion to a hot plasma ion Bernstein wave are dynamically calculated along the ray trajectory. We find the ray tracing analysis gives good agreement with the experiment in several respects: the density, magnetic field and plasma location where ion heating occurs in the octupole is consistent with the results of the ray tracing predictions. Along the ray trajectory the parallel index of refraction for some of the rays increases in qualitative agreement with that predicted from the data. Finally, the ray tracing predicts coalescence of the fast and slow lower hybrid branches for certain points along the ray. This is consistent with the experimental observation of the presence of both modes in the machine.

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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.

[1]McDonnell Douglas Corporation (at ORNL).

[2]T. L. Owens, J. E. Scharer, Nucl. Fusion 19 (1979) 1247.

[3]D. B. Batchelor, R. C. Goldfinger, Oak Ridge National Laboratory Report ORNL/TM-6844 (1982).

# FINITE LARMOR RADIUS EFFECTS ON STABILITY AND HEATING OF SCREW- AND REVERSED-FIELD PINCHES*

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Within the context of the Vlasov-fluid model,[1] a dispersion functional for a diffuse, straight screw pinch has been derived in an expansion of the reciprocal Vlasov operator. The expansion allows for arbitrary values of eigenfrequency divided by ion gyrofrequency, but restricts applicability to small ion gyroradii, in units of the gradient scale length of the eigenfunction. Reversed-Field Pinch (RFP) configurations are included in the analysis. An important aim of the present work is to investigate the possibility for rf heating of various pinch devices through a comparative study. Also, finite Larmor radius effects on stability of pinch equilibria with arbitrary shear and pitch profiles have never been investigated before. It is of interest, therefore, to apply the present formalism to determine the influence of finite ratios of the ion gyroradius divided by either the shear length and/or the pitch length. A comparison with a guiding-center code[2] in the appropriate limit is under way.

References

1. J. P. Freidberg, Phys. Fluids 15, 1102 (1972).

2. J. Choe, J. A. Tataronis, and W. Grossmann, Plasma Phys. 19, (1977).

*Work performed under the auspices of the USDOE.

# Gyroscopic Stabilization of a Spheromak Plasma Configuration

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Simple analytical models based on both force balance and energy principle analyses have been developed for and utilized in a study of the gyroscopic stabilization of spheromak tilting. It proposed that stability to shifting in a gyroscopically tilt stabilized spheromak can be achieved via proper field shaping without resorting to cumbersome devices such as close-fitting conducting shells, coils, or beam particles which do not appear to be valid "long-run" solutions to the tilt/shift stability problem.

The toroidal spheromak plasma can be regarded as a magnetic dipole aligned against the externally applied equilibrium field. By flipping over, the dipole can go into a state of lower energy. A "gentle" toroidal rotation of the plasma (e.g., $v_\phi(\text{rotation}) < 0.1\ v_{\text{thermal}}$) will, however, provide a gyroscopic effect that will tend to inhibit such a flip.

In the force balance analysis, it is required for stability to tilting that the gyroscopic torque be greater than the magnetic moment torque such that[1]

$$v_{\phi max} \gtrsim (5/8\pi\mu_o)\ (B_e^2\ \Delta t/\rho R_p)\ , \qquad (1)$$

where $B_e$ is the applied equilibrium field (Tesla), $\rho$ plasma density (kg/cm$^3$), $R_p$ plasma radius (m), and $\Delta t$ the time of perturbing force.

In the energy principle analysis, on the other hand, one requires that the total energy differential (including magnetic, kinetic, and rotational energy) between tilted and untilted spheromak plasmas in a uniform equilibrium field be less than zero to obtain, for stability to tilting,

$$v_{\phi max} \gtrsim \left[1/4\mu_o(\tfrac{1}{5} + \theta(\varepsilon))\right]\ (B_e^2\ \Delta t/\rho_o R_o)\ , \qquad (2)$$

where $\rho_o$ and $R_o$ are density and radius at the magnetic axis, and $\theta(\varepsilon)$ indicates a series of higher order terms which is the correction due to the density profiles.

For the parameters of the pS-1c experiment, Eqns. (1) and (2) predict that the rotational energies are about 1~2% of the thermal energy of the plasma ions. The actual measurements indicate the rotations in the range of $1\% < v_\phi/v_{th} < 10\%$.[2] Thus, we view this as a possible feedback stabilization mechanism for controlling the tilt/shift stability problem. The stability windows for a given ratio of kinetic energy to the total energy as a function of aspect ratio, current peaking factor, and engineering beta, will be discussed.

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1. R. Olson, F. Wysocki, and M. Yamada, "Toroidal Rotation and Gyroscopic Stabilization of a Spheromak Plasma Configuration," unpublished internal report, PPPL (August 1981).
2. M. Yamada and F. Wysocki, Princeton Plasma Physics Lab., private communications, 1981-82.

Stabilization of Trapped Particle Modes in the Tara Tandem Mirror*

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Trapped particle modes have been predicted to be linearly unstable in tandem mirror devices [1]. We show that when the equilibrium radial electric field points inwards, such modes can be stable. Stabilization of modes having an azimuthal mode number m>1 results from the coriolis force seen by the plasma in the frame rotating with the local ExB velocity. In the dispersion relation this coriolis force contributes to the drive term and can thus cancel the curvature drive for properly chosen equilibrium radial electric fields. This additional term vanishes for the m=1 mode and thus cannot stabilize a simple mirror. In TARA, however, the m=1 mode is stable for a sufficiently large passing electron fraction due to the charge separation resulting from differing ion and electron bounce points [1]. Thus a tandem mirror configuration such as TARA can be made stable to trapped particle modes even though all central cell ions reflect in the axisymmetric central cell or plug axicell and only electrons pass beyond the plug into the minimum B "anchor".

In the model problem presented we assume a simplified square well field in which all central cell ions are trapped within the flutelike region of the eigenmode. We pursue an analysis in which the Vlasov equation is solved using a finite Larmor radius ordering following ref. [2]. The electron equations are similarly ordered and yield a charge separation term proportional to their passing density. (Electron FLR corrections are negligible). We present estimates of the passing density needed for such a stabilization mechanism and for the equilibrium radial potentials needed to stabilize the m>1 modes. TARA configurations using electron pumping in the axi-cell are shown to be more easily stabilized than such configurations with a thermal barrier.

(1) H. L. Berk, M. N. Rosenbluth, H. V. Wong, T. M. Antonsen, D. E. Baldwin, U. Texas Rept. IFS-59 (1982).
(2) M. N. Rosenbluth and A. Simon, Phys. Fluids 8, 1300(1965).

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# Gyrokinetic Particle Simulation and Nonlinear Drift Waves*

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The numerical scheme based on the conventional particle simulation techniques to solve the nonlinear gyrokinetic equations[1,2] has recently been improved by including the FLR effects of the order of $k_\perp \rho_i \sim 1$. It is accomplished by pushing particles in the guiding center coordinates rather than in the laboratory coordinates as originally proposed.[1] The new scheme requires the numerical representation of the gyrophase-averaged quantities. Details will be reported.

A 2 1/2-D particle code adopting the new scheme has been developed for studying nonlinear evolution of drift waves in slab geometry. We have found that the simulation plasma exhibits highly turbulent behavior with broadly-peaked frequency spectra at the saturation state. However, for a system with only a few linearly unstable modes, the plasma response is rather coherent in the nonlinear stage where nonlinearly excited modes play an important role. In order to understand the mechanisms involved in this case, a Vlasov-type mode coupling code has also been used for the investigation. It is found that the effects of nonlinear $\underset{\sim}{E} \times \underset{\sim}{B}$ for both electrons and ions, and electron velocity space nonlinearity are mainly responsible for the saturation of drift waves and their subsequent development. Details will also be presented.

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

[1] W. W. Lee, Phys. Fluids (to appear in February 1983 issue).
[2] D. Dubin, J. A. Krommes, C. Oberman, and W. W. Lee, PPPL-1969 (1982).

# ENERGY LOSSES BY THERMAL CONDUCTION IN FIELD-REVERSED CONFIGURATIONS*

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Field-reversed configurations (FRCs) are elongated compact toroids without toroidal field. In the absence of fluid instabilities, energy losses out of the separatrix volume from particle transport, thermal conduction and radiation eventually limit the FRC lifetimes. A 1-D steady-state numerical model is being developed to address the first two issues. Radiation is not considered. The fluid equations include classical as well as various anomalous resistivities. This analysis extends previous work[1] limited to particle transport only. An accurate solution requires a 2-D (r,z) time dependent model. A steady-state solution is a good assumption because "steady-state" profiles of the plasma parameters are reached in present FRC experiments on timescales short compared with the changes in global plasma parameters. The elongated nature of FRCs allows a 1-D (r) transport model where plasma parameters are maintained inside the separatrix by axial contraction while a steady-state flow of energy and particles is established outside the separatrix towards the ends of the coil. On closed and open field line regions, the axial (z) terms are first found approximately and included as various sources and sinks to obtain the radial fluid equations. These are then solved with the boundary conditions that radial fluxes of particles and energy vanish far away from the separatrix. This is the case in present experiments where the ratio of separatrix to wall radii $r_s/r_w$ is about 0.4 and where the radial flow of particles and energy is converted into axial flow on a scale length of a few ion-gyroradii. Cases where $r_s/r_w \sim 1$, of interest in future experiments, will be discussed.

*Work performed under the auspices of U.S. DOE.

1. M. Tuszewski and R. K. Linford, Phys. Fluids, 25, 765 (1982).

# MULTIPOLE STABILIZATION OF FIELD-REVERSED CONFIGURATIONS: A WHOLE LOTTA SHAKIN' GOIN' ON*

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Field-reversed configurations (FRCs) are typically observed to terminate because of a rotational instability that elliptically deforms the plasma cross-section so much that the plasma strikes the vacuum vessel walls. In three different experiments during the past year this mode has either been completely stabilized or greatly suppressed by the application of multipole fields. This work was first done at Osaka University and later at Math Sciences Northwest, Inc. and at Los Alamos National Laboratory. Shortly after the Osaka results were announced, a fluid theory describing multipole stabilization was presented by T. Ishimura of Osaka University.[1] In his work a dispersion relation is obtained by ignoring the explicitly time-dependent terms in the MHD equations. D. Harned has simulated this system with a 2.5 dimensional hybrid code and finds that multipoles can control the rotational instability, but that the process is quite dynamic.[2] It is easy to see why this problem is inherently dynamic. Assume that the plasma is rotating rigidly, and imagine that we are in a frame where the plasma is stationary. In this frame the multipole fields are seen to be spinning around at the rotation frequency, while the plasma responds at its own characteristic frequencies. The coupling of the plasma frequencies and the rotational frequency requires a dynamical treatment. This, of course, is hard. To study the physical effects that are involved in this system, I propose a simpler system that has the main features of the rotating FRC with multipoles. The model is

$$y_{tt} - c^2 y_{xx} - \Omega^2 y = 0$$

with initial conditions $y(x,0) = 0$, $y_t(x,0) = v(x)$ and boundary conditions $y(0,t) = 0$, $Ty_x(L,t) = ky(L,t)(1+\alpha \cos \omega_s t)$. This is the wave equation for a centrifugally unstable wire under tension, T, so that the wave speed is c in the absence of the unstable term (the Coriolus force stabilizes this system, so it has been left out). The term $y_{tt}$ represents the fluid inertia, the term $c^2 y_{xx}$ represents the fluid compressibility, and the term $\Omega^2 y$ represents the rotational instability driving force in the fluid system. The initial conditions are like the usual ones for linear MHD, the x=0 boundary condition corresponds to regularity at r=0 in the cylindrical system, and the boundary condition at x=L corresponds to the matching condition on the perturbed pressure at the interface between the rotating fluid and the vacuum multipole field, which is assumed to be excluded from the fluid. In the model I have set the force at the end of the wire, $-Ty_x$, equal to the force produced by a spring attached at the end of the wire; the spring constant is, however, time-dependent to model the time-dependent magnetic pressure produced by the multipole field. The dynamic properties of this model system will be discussed.

1. T. Ishimura, Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, 1982) (Baltimore meeting).
2. D. Harned, this meeting.

*Work performed under the auspices of the USDOE.

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# HOPF BIFURCATION IN KINETIC THEORY: APPLICATION TO A COLLISIONAL BEAM-PLASMA INSTABILITY*

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Relatively recent developments in nonlinear mathematics allow bifurcation phenomena in ordinary and partial differential equations to be analyzed in a unified (and rigorous) way. In physical terms, bifurcation theory studies transitions between distinct physical states. These transitions arise through the development of instabilities. Although this theory is not fully developed, for transitions from time independent equilibria it is sufficiently complete to be useful.

In plasma, the mechanism which destroys a stable equilibrium is frequently the onset of unstable collective oscillations. For dissipative systems this instability is a Hopf bifurcation, and for the simplest case, e.g. unstable oscillation at a single wavelength, a detailed analysis is possible.

For a simple model of the collisional beam-plasma instability, this analysis determines whether the oscillation saturates at small amplitude and describes the stability and dynamics of the saturated state. The plasma is modeled as a finite-length, one-dimensional electron plasma with dynamics given by the Vlasov-Poisson equations with a Krook collision term. By extracting the dynamics on the center manifold, the problem reduces to two dimensions without requiring the truncation characteristic of Galerkin methods. Analysis of the normal form for the two-dimensional problem yields the nonlinear dynamics of the instability.

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Helical Axis Stellarators with
Planar, Nearly Circular Coils*

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We have studied the properties of helical axis stellarator fields generated by planar, nearly circular coils, focusing particularly on the very simple configuration consisting only of toroidal field coils. Our method is an expansion about the helical axis of the coils, valid when the coil diameter is small compared to the length of a single stellarator period. We argue on physical grounds that this condition will be at least approximately satisfied for any device of interest. The fields are chosen to maximize the rotational transform, while maintaining the presence of a magnetic well and reasonably shaped flux surfaces. The large transform minimizes toroidal effects, and thus implies a large equilibrium critical $\beta$. It also implies that the vacuum field is well approximated by a straight helical field.

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# EFFECTS OF MAGNETIC SHEAR ON THE CURRENT-DRIVEN DRIFT-ALFVEN INSTABILITY

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We have previously pointed out the possible connection between the unstable coupling of drift and Alfven waves (for $V_{current} \sim V_{Alfven}$) and the observed phenomenon of self reversal in the toroidal reversed field pinch ZT-40.[1] To improve upon our local approximation analysis, we now consider the effects of the high current and attendant strong shearing of the field lines in ZT-40 on the stability properties and spatial structure of this mode. In this regard, we extend the analysis of Ueno, et al.,[2] who considered this problem for the somewhat milder parametric environment characteristic of tokamaks.

[1] N. A. Krall and N. T. Gladd, Bull. Am. Phys. Soc. 27, 1033 (1982).

[2] C. Ueno, H. Irie, T. Tange, T. Watanabe, and K. Nishikawa, J. Physical Society of Japan 47, 984 (1979).

# MONTE CARLO ORBIT CALCULATIONS IN ATF*

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A state-of-the-art set of computer codes now exists to perform orbit calculations for the ATF torsatron. All calculations are performed in field line coordinates. Fields are obtained either from the coil configuration and the Biot-Savart Law or from the Chodura-Schluter 3-D MHD code. Collisions are introduced via the operators of Boozer and Kuo-Petravic. Heating can be introduced by suprathermal beam-injected ions or by a local ICRH operator. Vectorization of the code allows following 64 particles simultaneously while requiring only 5% of the computer time used to follow 64 separate particles.

For typical ATF parameters ($T = 1$ keV, $n = 10^{14}$ cm$^{-3}$), the ion tail (which dominates transport) is well into the collisionless $\nu$ regime. The presence of a radial electric field ($e\Phi \sim 1\text{-}3$ kT) has a dramatic effect on reducing ion losses. With the same parameters, the electrons are typically in the $1/\nu$ regime.

Monte Carlo calculations help to refine and verify analytic transport coefficient models and interface with the radial transport codes. They supply information about loss cones in the presence of large orbits and radial E-fields. Radial ion and electron fluxes are calculated as a function of E to determine the ambipolarity conditions.

Also, a "ballpark" estimate of energy and particle containment times may be obtained. With no E-field, $\tau_E \sim 1$ msec but with a potential, this can increase an order of magnitude or more.

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# TOTAL RADIATION FROM ARGON EDGE PLASMAS

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Radiation cooling by puffed argon is being considered for controlling the edge plasma temperatures of Tokamaks and other MFE toroidal devices. At the lower temperatures encountered, argon radiation rates are not available. In order to obtain an accurate and readily usable description of total radiation emitted by argon edge plasmas for the purpose of simulating such systems a versatile model for atomic levels of neutral argon and first second and third argon ions has been adopted. Line and continuum emission are calculated for Tokamak edge plasmas parameters.

# DRIFT PUMPING AT BOUNCE RESONANCE FREQUENCIES IN TANDEM MIRRORS*

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Drift pumping is the removal of unwanted ions by stochastic radial drift motion induced by a time varying $E_\perp$ field. The scheme exploits the geometric features of the extreme fanning of the flux surfaces and relies on bounce-harmonic resonances which are excited by the z structure of the rf field itself, $E(z)$, the $B_0$ field through $E/B(z)$, and the fanning structure of the field lines, $X_0(z)$, $Y_0(z)$. We require an rf signal with frequency at one of the bounce harmonic resonances and with sufficient bandwidth to extend over both: (1) the range of bounce frequencies encountered by a single particle in its radial motion $\Delta\omega_z(r)$ and; (2) the range of bounce frequencies dictated by the total spectrum of pitch angles and energies of the trapped particle species. Since the rf signal is an m=1 mode ($\tilde{E}_\perp = E_y$), the resonant frequencies will be given by

$$\omega = n\omega_z \pm \bar{\omega}_D \quad , \qquad (1)$$

where $\bar{\omega}_D$ is the bounce average azimuthal drift frequency. We determine the spectral conditions required for stochasticity and describe diffusion in radius r and energy $\varepsilon$. The approximate radial diffusion coefficient is

$$D_r = \frac{1}{10} \frac{\omega_z^2}{\Delta\omega_z} \left( \frac{\tilde{B}_{1\mu}}{B} \right)^2 L^2 f \quad .$$

where $\tilde{B}_{1\mu}$ is the effective amplitude of the rf field at the first harmonic resonance, L is the coil length, and f is the flux tube ellipticity, and the approximate energy diffusion is

$$D_\varepsilon = (q\nabla_\perp \phi)^2 \, D_r \quad ,$$

where $\phi$ is the ambipolar potential. Analytic work has focussed on the condition for stochasticity, energetics, and characteristics of the 2D r,$\varepsilon$ diffusion. The numerical work to date has checked that bounce resonance harmonics do occur precisely at the value given by Eq. (1), and has observed that the fanning can be a strong enhancement. Also, stochastic orbits have been observed under some conditions. Calculations defining conditions for stochasticity and detailed diffusion measurements using an ensemble of orbits will be shown.

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# FLR MODIFICATION OF THE VARIATIONAL FORM OF THE EIGENMODE EQUATION FOR ELECTROMAGNETIC PERTURBATION OF INHOMOGENEOUS MAGNETIZED PLASMAS

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The variational form of the eigenmode equation, with inclusion of finite Larmor radius effects, is derived for low frequency, long wavelength, electromagnetic perturbations of inhomogeneous magnetized plasmas. The perturbed distribution function is determined by $f(\underset{\sim}{P},\underset{\sim}{r},t) = [F_0,W]$ , where $F_0$ is the equilibrium distribution function, and $W(\underset{\sim}{P},\underset{\sim}{r},t)$ is the solution of the equation

$$\frac{\partial W}{\partial t} + [W,H_0] + H_1 = 0 \quad .$$

W is obtained by a perturbation expansion in the Larmor radius. Cartesian tensors are employed to write in a compact form the terms appearing in the perturbation series. Variational quadratic forms are then constructed by evaluating

$$\langle f H_1^{\dagger} \rangle = \langle [F_0,W] H_1^{\dagger} \rangle$$

where $\langle\ \rangle$ implies integration over all phase space and the superscript + denotes the adjoint function.

# SPECTRAL PROPERTIES OF THE KINETIC ALFVEN WAVE IN TOKAMAK GEOMETRY*

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and Y-T. Yan (William & Mary)

Recently, Tsang et. al.[1] have studied the effects of 1st order FLR on the radial Alfven eigenmode and showed that in cylindrical geometry, at the Alfven resonance point $\omega^2 = c_A^2 k_{||}^2(r)$, the continuum is destroyed and is replaced by a discrete spectrum.

However, Connor et. al.[2] have considered the effects of higher order FLR--but in a slab geometry, assuming $k_{||}(x) = k'_{||} \cdot x$. They find that the 1st order FLR discrete spectrum is replaced by a continuum if one keeps the complete (infinite order) FLR effects.

It is thus of considerable interest to investigate the higher order FLR effects in cylindrical geometry. Assuming, following Tsang et. al., that $k_{||}(r) = k_o + k_1 r^2$, $k_o \neq 0$ one finds, on using asymptotic analysis, a discrete spectrum to all orders in FLR. Numerical work will be presented to substantiate this result.

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* Work supported by DOE

[1] K. T. Tsang, D. J. Sigmar and J. C. Whitson, Phys. Fluids <u>24</u>, 1508 (1981).

[2] J. W. Connor, W. M. Tang, and J. B. Taylor, Phys. Fluids <u>26</u>, 158 (1983).

# AN ANALYTICAL CALCULATION OF THE TRAPPING RATE IN THERMAL BARRIERS*

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A previous variational calculation of the trapping rate and the trapped ion density in a thermal barrier(1) is improved. Analytical expressions for the pumping factor, $g_b$, and therefore for the trapping rate and the trapped ion density are given as a function of five input parameters: passing ion density, passing ion temperature, mirror ratio, potential dip in the barrier, and the neutral beam pumping rate. On the hyperbolic boundary separating the passing and trapped particles in phase space, the trapped ion distribution function matches the passing ion distribution function. The effects of diffusion in energy as well as pitch angle scattering are retained.

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* Research supported by Department of Energy.

(1) X.Z. Li and G.A. Emmert, University of Wisconsin Fusion Engineering Report UWFDM-490 (1982).

# VLASOV STABILITY OF A ONE-DIMENSIONAL FIELD-REVERSED THETA PINCH*

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A code, based on the formulation of Lewis, Symon and Seyler,[1-4] has been written for stability analysis of general one-dimensional, cylindrically symmetric, spatially inhomogeneous, two-species Vlasov equilibria. In this application we are studying global microstability properties associated with steep radial gradients in equilibrium profiles in the midplane of a field-reversed theta pinch. (In the midplane region the magnetic field lines are nearly straight, so that the equilibrium can be treated as if it were one-dimensional.) No approximations are made except numerical ones. We shall present preliminary results that probe the computational feasibility of this exact stability analysis.

References

1. H. R. Lewis and K. R. Symon, J. Math. Phys. 20, 413 (1979); Erratum J. Math. Phys. 20, 2372 (1979).

2. K. R. Symon, C. E. Seyler, J. Plasma Phys. 27, 13 (1982).

3. H. R. Lewis and C. E. Seyler, J. Plasma Phys. 27, 25 (1982).

4. C. E. Seyler and H. R. Lewis, J. Plasma Phys. 27, 37 (1982).

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# QUASISTATIC EVOLUTION AND STABILITY OF A COMPACT TOROID*

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We consider the equilibrium, stability, and transport of a compact toroid within the context of a model in which inertia is neglected and the plasma evolves through a sequence of quasiequilibrium states while the profiles of magnetic field, density, temperature, etc. evolve due to diffusion.

We compute the evolution of both force-free and finite-$\beta$ plasmas and compare with experimental observations. These observations show periods during which the plasma evolves on the diffusive timescale intermixed with evolution on the dynamic timescale. We test the equilibria for stability using a linear stability code and compare the time of instability predicted by simulation with the times during which the experiment evolves on the dynamic timescale.

*Work performed under the auspices of the USDOE.

Theoretical Modeling of ICRF in Reactor Size Plasmas,*
R. J. Kashuba, P. L. Colestock, J. F. Pipkins.
McDonnell Douglas Corp. --The fast magnetosonic wave can be efficiently excited at the plasma edge and may be subsequently damped at the cyclotron layer or coupled to ion Bernstein waves via mode conversion. This results in effective plasma heating at the minority fundamental resonance and at the majority second harmonic resonance. We examine the scaling of this heating scheme to reactor type plasmas using a slab model with a hot plasma dielectric. In addition we will present the effects of trapped particles and a two-dimensional damping model on the heating process. While we have found that wave absorption is sufficiently strong to approach the black body limit, geometric factors can play an important role in determining actual power deposition profiles. Therefore the results of the damping model are included in a three dimensional field calculation which includes both radial and toroidal field gradients.

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# Linear and Nonlinear Study of Ideal Internal Kink Modes*

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The usual tokamak expansion in inverse aspect ratio, $\varepsilon$, is carried out to leading plus the next two orders for a low beta scaling [$\beta \sim 0(\varepsilon^2)$]. This fourth order, reduced set of MHD equations is solved numerically in three dimensions to study the stability characteristics of the ideal internal kink mode by extending the initial value code HIB. This newer version is referred to as HILO.

In leading order, $0(\varepsilon^2)$, reduced MHD predicts marginally unstable m=1 kink modes at zero beta. The next order corrections are stabilizing toroidal effects. Fourth order terms yield the leading order growth rate for low $\beta$ plasmas. The equations uniformly go over to a third order accurate set for high beta plasmas. Thus, the formulation is such that we may study the stability characteristics of the m=1 internal kink for all beta.

Linear growth rates have been computed for both cylindrical and toroidal geometries. For the cylindrical case, HILO gives excellent agreement with growth rates computed from the exact, linearized MHD equations. For the toroidal case, linear growth rates are compared with PEST-1 results.

HILO is used to study the nonlinear evolution of PDX plasmas to better understand observed MHD oscillations.

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# Group Theory Approach to the One-Dimensional MHD Equations

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## ABSTRACT

We are considering a one-dimensional nonstationary plasma with finite electrical resistivity $\eta = Ap^{-m}(x,t)\rho^{-n}(x,t)$, where $A,m,n \in R$ and $p$ and $\rho$ are the thermodynamic pressure and mass-density, respectively. Viscosity effects and heat conductivity are neglected. The magnetic-field has only one component $B(x,t)$ in the z-direction of a Cartesian coordinate system. In order to find special solutions for the set of MHD-equations (including the energy equation) [1], we are dealing with one-parameter Lie-groups [2], which leave invariant the one-dimensional MHD equations. The infinitesimal generators of the corresponding Lie-algebra are determined and the functional forms of so-called invariant solutions are obtained for special cases. The classical similarity solutions are a subset of the invariant solutions. If the adiabatic exponent $\gamma$ is different from two, the invariant solutions depend on five arbitrary parameters. If $\gamma = 2$ and $m = 0$, they depend on one more arbitrary parameter.

[1] S.I. Pai, Magnetogas dynamics and Plasma Dynamics, Springer-Verlag, 1962.

[2] L.V. Ovsjannikov, Gruppovye Svoystva Differentsialny Uravneni, Novosibirsk, 1962.

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ABSTRACT SUBMITTED TO
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Suggested Session:
TRANSPORT

A Generalized Fokker-Planck Equation: The Inclusion of the Nuclear and Coulomb-Nuclear Interference Cross Sections ($\sigma_{NI}$) in the Small Angle Scattering Regime*. A. Andrade and G. M. Hale Los Alamos National Laboratory — Estimates of the effects of including the total elastic scattering cross section in the small angle regime are being investigated[1] since recent work[2] has shown that $\sigma_{NI}$ makes a small but significant contribution. Here, a general Fokker-Planck equation is presented which includes $\sigma_{NI}$ analytically and calculational examples are given.

1. S. T. Perkins and D. E. Cullen, Nucl. Sci. Eng. 77, 20(1981).

2. G. M. Hale, D. C. Dodder and J. C. DeVeaux, "Charged Paricle Elastic Cross Sections," presented at the International Conference on Nuclear Data for Science and Technology, 1982.

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# Nonlinear Fluid Models for Tokamak

# Plasma Dynamics

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The effectiveness of reduced MHD[1] in interpreting nonlinear processes in tokamak plasmas has prompted several extended versions[2], which attempt to incorporate various kinetic and diamagnetic effects. Two new models are presented here. The first is quite simple: it involves no additional fields beyond those of (high beta) reduced MHD and contains only quadratic nonlinearities. The second, more elaborate, model uses additional fields to describe sound wave propagation and electron kinetic refinements associated with thermal transport. Both models are derived from systematic application of a modified reduced MHD ordering, which provides closure of either exact or otherwise appropriate[3] moment equations. Thus, in particular, important gyroviscous effects are treated carefully. In linear theory, the models reproduce crucial features of the electron kinetic theory, including a physical collisionality ($\nu/k_{\parallel} v_e$) dependence of the conductivity. Toroidicity-induced return current (compressibility), non-linear diamagnetic convection and current gradients are also treated consistently. Both models are shown to reproduce surprisingly well such important nonlinear processes as transport due to stochastic magnetic fields. A generalized Hasegawa-Mima equation[4] is obtained in the appropriate limit.

This work has been supported by DOE Grant #DE-FG05-80ET-53088.

1. H. R. Strauss, Phys. Fluids 20, 1354 (1977).
2. For example: D. Edery et al., EUR-CEA-FC-1013 (1979); J. F. Drake et al., Bull. Am. Phys. Soc. 27, 912 (1982).
3. A. B. Mikhailovskii, JETP 25, 623 (1967).
4. A. Hasegawa and K. Mima, Phys. Fluids 21, 87 (1978).

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# SOME COMMENTS ON THE MINIMUM ENERGY HELICAL STATE FOR REVERSED=FIELD PINCHES

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While the F-$\Theta$ curve for a symmetric state has occupied the attention of most experimenters on the reversed-field pinch, following the work of Taylor [1] and Reiman [2], very little attention has been given to the helical state. Yet in nearly all the present reversed-field pinch experiments, the volt-seconds applied are so high that only the helical state is relevant. This is precisely why constant-$\Theta$ operations are frequently observed [3].

We examine in detail the nature of the helical state as given by Reiman [2]. We conclude that while $\Theta = 3.11$ is the theoretical value for an infinitely long cylinder, actual toroidal pinches approximated by cylinders will operate with $\Theta$ near to but not equal to 3.11; the precise value is determined by the toroidal mode number $k$ such that an integral number of helices will fit into the device. The discreteness of the eigenvalues, the poloidal mode number $m$, etc. are reexamined. The amplitude of a helix to be observed in an experiment are explicitly calculated from energy integrals.

[1] J.B. Taylor, Proc.5th IAEA Controlled Fusion Conf. (Tokyo), 1975. Vol. I, 161.

[2] A. Reiman, Phys. Fluids 23, 290 (1980); 24,956 (1981).

[3] K. Ogawa et al, paper IAEA-CN-41/H1, ZT-40 team, paper IAEA-CN-41/H2-1, 9th IAEA Controlled Fusion Conf (Baltimore), 1982.

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# TIME-DEPENDENT HYDRODYNAMIC PLASMA-WELL CALCULATIONS

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Virtually all codes modelling plasma-wall interactions assume steady-state modes of operation. Recent calculations[1] with a stationary fluid model including the same physical effects used here and described below indicate that stationary, solutions may not exist above about 5 eV, except perhaps with the assumption of strong pumping. Non-steady-state behavior may thus be important in these cases in which in refluxed particles destabilize the plasma. We are presently investigating such possibilities via a 1-d fluid model including ion thermal conduction, plasma viscosity, pumping, thermal cross-relaxation between electrons and ions, omission of neutral hydrogen from the solid surface, and electron impact ionization of this neutral hydrogen. Time-dependent results will be presented for a variety of physical boundary conditions.

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1. Sowers, et al, presented at this conference.

# STATIONARY WALL PLASMA STRUCTURES IN THE LOWER TEMPERATURE, FLUID MODEL REGIME

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Structures of wall plasmas near divertor neutralizer plates or limiters are calculated using a fluid model. Effects of ion thermal conduction, plasma viscosity, thermal cross relaxation between electrons and ions, ionization of neutral hydrogen emitted from the solid wall, and some pumping removal of these neutrals are included. This fluid model is thought to be applicable near or below scrape of plasma temperatures of about 20 eV. Stationary solutions which satisfy physical boundary conditions are found for scrape off temperatures below approximately 6 eV.

1. Now with Arizona Public Service, Phoenix, Arizona.

# LONG-TIME BEHAVIOR FOR INVERSE CASCADES IN FINITE SYSTEMS*

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Speculations about inverse cascades have often been formulated in the context of idealized infinite systems, with no lower bound in wavenumber space to stop the expanding spectrum at the lower end. In either a real system or a computer simulation, a minimum wave number must exist because of the finite size of the system. As the fundamental fills up, there are several imaginable scenarios for what might happen: e.g., (1) the inverse spectral transfer to long wavelengths might cease; (2) the inversely transferred quantity might distribute itself according to a power law with a gradually temporally increasing constant multiplier between the fundamental and the forcing band; or (3) the fundamental might continue to grow and gradually leave the other wavenumbers behind. By running both 2D Navier-Stokes and 2D MHD spectral codes much longer than previously, we have seen what we believe is an answer to this question: (3). Eventually, the fundamental comes to dominate completely the spectral distribution of the inversely cascaded quantity.

* Work supported in part by USDOE and NASA.

# DRIFT RIPPLING MODES*

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A model based on the rippling mode turbulence has been proposed to explain the edge transport of tokamak.[1] For simplicity, only finite parallel thermal conduction was included in the model. However, other effects must be included in the model to have a complete physical description.[2]

A reduced system of equations, valid for low $\beta$, cylindrical geometry, has been derived from the two fluid equations.[3] This system includes terms such as diamagnetic drifts, viscosity or thermal force, and can be used for linear and nonlinear calculations.

We have done linear stability calculations, including the effect of $\omega_*$. The growth rates compare favorably with the analytical dispersion relation. Calculations are in progress for realistic tokamak parameters. Results will be presented at the meeting.

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

[1]"Edge Turbulence in Tokamaks," J.D. Callen, B.A. Carreras, P.H. Diamond, M.E. Benchikh-Lehocin, L. Garcia, and H.R. Hicks. Proceedings of the 9th International Conference of Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Vienna). To be published.

[2]A. B. Hassam and J. F. Drake, Phys. Fluids 26, 133 (1983).

[3]S. I. Braginskii, "Reviews of Plasma Physics," edited by M. A. Leontovich Consultants Bureau, New York, 1965) Vol. I, p. 205.

# ALFVÉN ION-CYCLOTRON INSTABILITY IN TANDEM-MIRROR PLASMAS*

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A variety of magnetic-mirror cells is susceptible to the Alfvén ion-cyclotron (AIC) instability. These cells range from the end cells of the Tandem Mirror Experiment[1] to cells with sloshing ions in present experiments[2] to long central cells with multiple species in reactor designs.[3] Possible effects of AIC instability in a tandem-mirror device include enhanced ion loss rates, perpendicular heating, and thus trapping, of ions passing through the bad-curvature regions between the central and end cells, and the perhaps beneficial heating of the central cell.

Our linear stability theory for the AIC mode now treats axial nonuniformity (by WKB methods) and multiple species with almost arbitrary distribution functions; we solve self-consistently the long-thin equilibrium relation. Numerical results show that each of the following stabilizing effects is important in some mirror cell: (a) oblique neutral-beam injection (forming sloshing ions), (b) cyclotron damping by cool ions with parallel temperature exceeding that of the hot ions, (c) mixing hot ions of two or more species, and (d) finite plasma length. This knowledge helps us avoid deleterious effects of AIC instability in tandem mirrors.

[1]T. A. Casper and G. R. Smith, Phys. Rev. Lett. 48, 1015 (1982).
[2]T. C. Simonen, et al., UCRL-88266, Nov. 1982 (to be published in Phys. Rev. Lett.).
[3]J. D. Hanson and E. Ott, U. of Maryland Report 83-062, Oct. 1982.

*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.

# MHD Equilibrium and Stability of Finite Beta Tandem Mirrors

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## ABSTRACT

Finite beta equilibria and low mode number ballooning stability have been computed for TMX-U, MFTF-B, and TARA magnetic fields. Results were obtained numerically solving long thin ordered, tensor pressure, high beta, reduced MHD equations of motion [1,2,3]. Principal findings are as follows:

1) Equilibrium. The m=4 flux surface distortions in the central cell, which might enhance radial transport, agree in sign with Stupakov [4], but are generally small. The m=2 distortions outside the central cell are typically much larger. The distortions are severe in TARA if the transition beta is 10%, but moderate for the planned 1%.

2) Stability. Beta limits for m=4 ballooning/interchange modes have been found to be only moderately affected by finite beta. The anchor cells by themselves can stably support beta of order unity. The beta limits for m=4 ballooning/interchange modes are generally comparable to the large m results on the "best" field line. Stable TMX-U equilibria were found with central cell beta of 60%, and stable MFTF-B equilibria with central cell beta of 30%.

[1] H. Strauss, N.F. (1982).
[2] W.A. Newcomb, J. Plasma Phys. 26, 529 (1981).
[3] H, Strauss, S. Wollman, M. Wakatani, submitted to P.F.
[4] G.V. Stupakov, Sov. J. Plasma Phys. 5, 486 (1979).

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# A COMPARATIVE STUDY OF A d-d AND A d-t TANDEM MIRROR

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Advanced fusion fuels, i.e., fusion fuels based on cycles other than d-t, have been suggested as fuels for fusion reactors of the future. Such support is mainly based on safety issues, such as low activation of reactor materials and the relaxation of the requirement for tritium breeding that one needs for a d-t fusion reactor.

Nevertheless, the lower fusion reaction rates and the higher required operating temperatures of these advanced fuels have suggested that reactor performance would be inferior to that of a d-t reactor. Some recent results[1-3] have tended to confirm this conclusion.

However, a comparative study of a d-d and a d-t tandem mirror reactor has been performed, illustrating major physics issues, that indicates that the performance gap between the two reactors may not be significant. Although the plasma radius, the central cell length, and the average temperature of the d-d TMR are greater, the densities and magnetic fields are such that the peak plasma betas are the same and the central cell magnet bore and the end magnets are comparable. Detailed MHD equilibrium and stability studies are performed, as are self-consistent power balance computations to determine the plug and barrier ambipolar potentials that are required for confinement. It is found, for example, that the synchrotron radiation power loss, even at the near relativistic temperatures of the electron plug, does not prevent favorable performance of the d-d TMR.

Since the d-d TMR has a larger fraction of its reaction energy in charge particles, one is able to take advantage of the higher efficiency direct conversion, in addition to the thermal conversion from neutrons. The overall plant efficiency is higher for the d-d TMR and the resulting capital costs per net power output is within 20% for the two reactors studied. The safety advantages of the d-d TMR are confirmed. Although the d-d TMR still requires tritium handling, its inventory is considerably less than that of a d-t TMR.

[1] J. D. Gordon et al., "Evaluation of p-Based Fuels for Fusion Power Plants," EPRI Report, RP 1663-1, 1981.

[2] R. W. Conn et al., "SATYR: Studies of a d-d Axisymmetric TMR," UCLA Report, PPG-576, September 1981.

[3] K. Evans, Jr., et al., "WILDCAT: A Cat-d Tokamak Reactor," ANL/FPP/TM-150, November 1981.

# STRUCTURES OF WALL PLASMAS NEAR DIVERTOR NEUTRALIZER PLATES AND LIMITERS

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At scrape off layer edge plasma temperatures above about 20 eV., it has been found to be necessary to employ a self consistent kinetic transport model, including plasma chemistry, to calculate divertor and limiter wall plasma structures. These higher temperatures now appear to be particularly interesting because of H mode operation of Tokamaks. These structures are calculated in order to estimate removal of heat and impurities and rates of sputtering of wall surfaces. Earlier work by the authors[2] has been considerably extended to include additional collision effects and details of the non-neutral region near the wall. The resulting self consistent electrostatic potential, $\phi$, has a peak away from the wall, a decrease of less than $kT_e$ going back toward the main plasma, and a Debye sheath drop on the wall side of order 4 $kT_e$. Consequently, some of the neutral hydrogen emitted from the wall is ionized before reaching the peak of $\phi$ and is returned to the wall; the remainder is ionized beyond the peak of $\phi$ and recycled toward the main scrape off plasma. The wall sputtering caused by the hydrogen returned to the wall and that which is incident from the main plasma and passes over the peak of $\phi$ is calculated and presented in an accompanying paper by McKenty, et al. The distribution of velocities of ions and neutrals returning toward the main plasma have distinct, non maxwellian forms which should be experimentally observable.

1. Plasma Fusion Center, MIT.

2. Phys. Rev. Lett. 49, 650(1982).

# PARAMETRIC INSTABILITIES DURING ELECTRON CYCLOTRON HEATING OF TANDEM MIRRORS

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Electron cyclotron resonance heating is one of the most commonly used methods of heating electrons in the plugs and in the thermal barriers of tandem mirrors. The intense coherent electromagnetic waves used for such heating are susceptible to parametric decay into other modes. Significant growth rates are found[1,2] for the decay of either ordinary or extraordinary waves into two magnetized electron plasma waves. This and related effects may result in electron heating mechanisms rather different than those assumed in linear ray-tracing calculations. These results could help explain the unusual effects observed during heating of Phaedrus.[3] In the general case, these instabilities may be strongly inhibited by density gradients.[4]

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[1] H. C. Barr, T. J. M. Boyd, and L. R. T. Gardner, "The Raman and Two Plasmon Decay Instabilities in a Magnetized Plasma," Phys. Fluids, 26 (1983), in press.

[2] D. R. Nicholson, "Parametric Instabilities During Electron Cyclotron Heating of Tandem Mirrors," preprint U. of Iowa 83-2, submitted to Nuclear Fusion.

[3] J. Kesner, R. S. Post, and D. Smatlak, private communication.

[4] C.-S. Liu and M. Rosenbluth, Phys. Fluids, 19, 967 (1976).

# A NEW LONG MEAN FREE PATH RESISTIVE MHD INSTABILITY*

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In the banana-plateau regime where most tokamaks operate, the (parallel) electron viscosity damping rate[1] ($\mu_e \sim \epsilon^2\omega_{be}$ in the plateau regime) of poloidal flows is larger than the growth rate or diamagnetic drift frequency of medium mode number ($n \sim 3$-$20$) resistive MHD modes. However, in the usual collisional ($\nu_e > \omega_{be}$) resistive MHD picture, pressure fluctuations induce a primarily poloidal flow $\underline{\tilde{V}}_\perp = \underline{B} \times \underline{\nabla}\tilde{p}/nqB^2$; the divergence of the corresponding perpendicular current is the primary drive for resistive-g and resistive ballooning modes. The strong electron viscous damping of poloidal flows in the banana-plateau regime causes, in analogy with neoclassical transport theory,[1] a fluctuating "bootstrap" current $\tilde{J}_\parallel = -(c/B_p)(\mu_e/\nu_e)(d\tilde{p}/dr)$ contribution to the perturbed parallel Ohm's law. This produces a new type of "long mean free path" resistive MHD instability that has: 1) $\tilde{p}$ odd, $\tilde{J}_\parallel$ even about a rational surface -- tearing mode parity; 2) $\gamma\tau_R \sim S^{2/3}n^{2/3}e^{-i\pi/6}(\beta_p q^2\mu_e/\nu_e)^{2/3}$ -- similar to resistive ballooning mode scalings and magnitudes[2]; 3) inferred anomalous transport coefficients similar to those due to resistive ballooning modes[2] with $\beta/\epsilon$ replaced by $\beta_p(\mu_e/\nu_e)$; 4) parallel current fluctuations comparable to the neoclassical bootstrap current thus vitiating the equilibrium bootstrap current. Since many features of the new mode scale as $\mu_e/\nu_e \sim 1/n_e$, there is some possibility that Alcator-like $\tau_E \sim n_e$ scalings may emerge from plasma confinement in the presence of these modes. The formal analysis proceeds by utilizing a Grad 13 moment representation for the distribution function (to include the viscosity effects) and a multiple time scale (finite gyroradius) expansion in a ballooning mode representation with a subsidiary expansion in $(\gamma, k_\parallel v_{Te} \lesssim \mu_e)/(\nu_e, \omega_{be}) \sim \delta \ll 1$.

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1 S.P. Hirshman and D.J. Sigmar, Nuclear Fusion 21, 1079 (1981).

2 B.A. Carreras, P.H. Diamond, et al., Phys. Rev. Letters 50, 503 (1983).

# LINEAR AND NONLINEAR NUMERICAL STUDIES OF MAGNETIC FLUCTUATIONS IN ETA-BETA-II

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Magnetic fluctuations are a dominant experimental signal in many reversed-field pinches (RFPs). They are thought to be responsible for the observed dynamo effect[1], and may represent a significant transport mechanism.[2] Recent experimental studies on the ETA-BETA-II device at Padua have yielded detailed internal and external measurements of these fluctuations.[3] We are using linear[4] and nonlinear[5] MHD codes to study these fluctuations in detail.

By fitting splines to the experimental points, we have determined reasonable radial magnetic field and pressure equilibrium profiles, which are then studied for linear stability. The resulting unstable spectrum is then used as an initial perturbation for three-dimensional, nonlinear simulations, and the resulting fluctuations are compared to the experimental measurements. Preliminary results of this study are presented.

[1] R. G. Watt and R. A. Nebel, LA-UR-83-13, submitted to Phys. Fluids (1983).

[2] T. C. Hender and D. C. Robinson, in Workshop on Comp. MHD Models of the Behavior of Mag. Confined Plasmas, Wildhaus (1981).

[3] V. Antoni and S. Ortolani, submitted to Plasma Phys. (1982).

[4] J. P. Freidberg and D. W. Hewett, J. Plasma Phys. 26, 177 (1981).

[5] D. D. Schnack and E. J. Caramana, Proc. Tenth Conf. on Num. Simulation of Plasmas, page 2B12, San Diego (1983).

# UNSTABLE-UNSTABLE PAIR BIFURCATION AND CHAOTIC TRANSIENTS*

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In this work we demonstrate a new type of bifurcation to chaotic motion. This bifurcation is characterized by:

(1) the simultaneous appearance of a pair of unstable fixed or periodic orbits (here called unstable-unstable pair bifurcation);

(2) the occurrence of a chaotic attractor and a fractal basin boundary;

(3) a chaotic transient that can be extremely long-lived.

The unstable-unstable pair production route to chaos can only occur in systems of at least four autonomous differential equations, three dimensional invertible maps, or two dimensional noninvertible maps.

To illustrate the new type of bifurcation to chaos, we consider a two dimensional noninvertible map. At the crisis[1,2] value $\alpha = \alpha_c$ of the parameter there is an unstable-unstable pair bifurcation at which the chaotic attractor and its basin are created or destroyed. This bifurcation is one of the manifestations of the crisis route to chaos when the chaotic attractor, which exists in this case for $\alpha < \alpha_c$, is replaced by a chaotic transient for $\alpha > \alpha_c$. Inversely, a chaotic transient becomes a chaotic attractor for $\alpha = \alpha_c$.

The remarkable aspect of this type of bifurcation is that the chaotic transient can be extremely long-lived. For example, even at a value of $\alpha$ of the order of 20% above $\alpha_c$, the transient is of the order of $10^4$ iterates. The existence of such exceedingly long chaotic transients may have important implications in experiments on chaotic systems.

1. C. Grebogi, E. Ott, and J. A. Yorke, Phys. Rev. Lett. 48, 1507 (1982).
2. C. Grebogi, E. Ott, and J. A. Yorke, Physica D (in press).
* Work supported by DOE (Office of Basic Energy Sciences) and AFOSR.

# FRACTAL BASIN BOUNDARIES*

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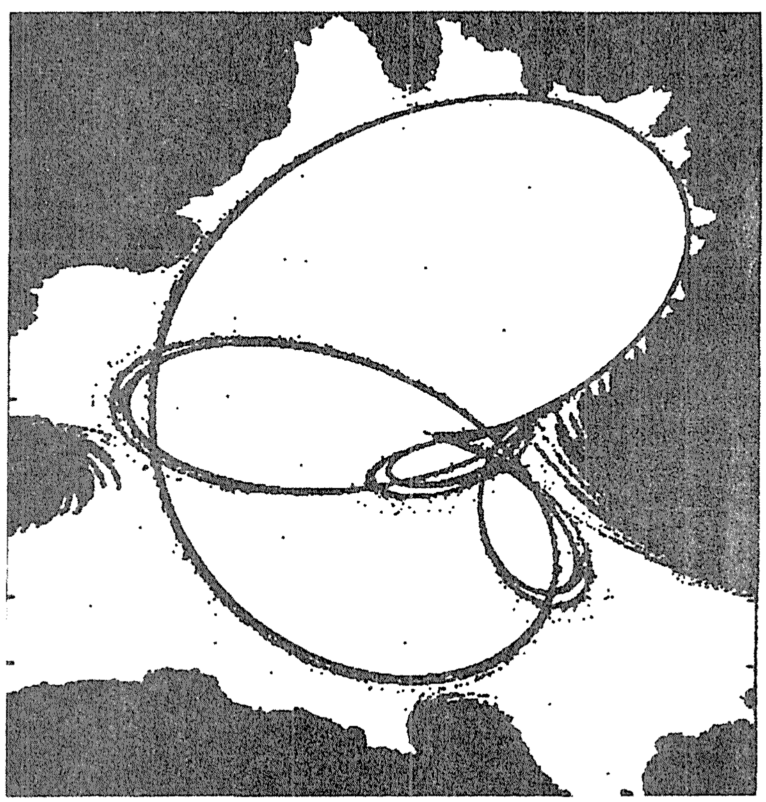
A common situation in dissipative dynamical systems is the coexistence of more than one attractor. Associated with each attractor is a basin of attraction, i.e., the set of initial conditions which asymptotically approach the attractor. In this work we investigate the structure of the boundaries separating basins of attraction. Previous studies have shown that a basin boundary may consist of a single point (in one dimensional maps), a smooth curve (in two dimensional invertible maps[1]) or possibly a fractal curve.[2]

In this paper we use simple model maps to demonstrate the existence of fractal boundaries and to examine their properties. The accompanying figure shows a strange attractor, its basin of attraction (blank region), and the basin of attraction for another attractor (black region). The boundary between these regions is fractal.



1. C. Grebogi, E. Ott, J. A. Yorke, Physica D (in press).
2. G. Julia, J. Math. Pre Appl. 4, 1918.

* Work supported by DOE (Office of Basic Energy Sciences) and AFOSR.

# Three Dimensional Ballooning Mode Stability for Stellarators

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We have developed an efficient way to compute ballooning mode and Mercier stability for a stellarator configuration of moderate beta. The method relies on utilizing a vacuum field line solver due to a given set of coils. Then given a Clebsch representation of the magnetic field, $\underset{\sim}{B} = \underset{\sim}{\nabla}\alpha \times \underset{\sim}{\nabla}\beta$, and using the standard for toroidal angle, $\phi$, as the third coordinate, one can express the ballooning mode equation in terms of the contravariant vector $\underset{\sim}{e}_3$, where differential displacement is given by $d\underset{\sim}{r} = \underset{\sim}{e}_1 d\phi + \underset{\sim}{e}_2 d\alpha + \underset{\sim}{e}_3 d\beta$. To within a normalization factor, $\underset{\sim}{e}_3$ is then the difference of two neighboring points on the same flux surface at constant $\phi$. This vector is easily calculated from a field line following code. The ballooning mode Euler-Lagrange equation in this representation is found to be,

$$\frac{d}{d\phi}\left[\frac{B_\phi}{B^2 R}\left(\frac{1}{|\underset{\sim}{e}_3\times\underset{\sim}{b}|^2} + B^2\Lambda^2|\underset{\sim}{e}_3\times\underset{\sim}{b}|^2\right)\right]\frac{d\xi}{d\phi} + 2\frac{\partial p}{\partial\alpha}\left[\frac{\underset{\sim}{e}_3\times\underset{\sim}{b}\cdot\underset{\sim}{\kappa}R}{B_\phi|\underset{\sim}{e}_3\times\underset{\sim}{b}|^2} - \Lambda\frac{d\lambda}{d\phi}\right]\xi = 0$$

with

$$\frac{d\Lambda}{d\phi} = \frac{R}{B_\phi}\left\{\frac{\left(\underset{\sim}{e}_3-(\underset{\sim}{e}_3\cdot\underset{\sim}{b})\underset{\sim}{b}\right)}{|e_3\times b|^4}\cdot\left[\underset{\sim}{b}\cdot\underset{\sim}{\nabla}(\underset{\sim}{e}_3\times\underset{\sim}{b})-(\underset{\sim}{e}_3\times\underset{\sim}{b})\cdot\underset{\sim}{\nabla}\underset{\sim}{b}\right] - \frac{2\partial p}{\partial\alpha}\frac{(\lambda-\langle\lambda\rangle)}{|e_3\times b|^2}\right\},$$

and

$$\frac{d\lambda}{d\phi} = \frac{R}{B_\phi}\underset{\sim}{e}_3\cdot\underset{\sim}{\kappa},\quad \langle\lambda\rangle = \lim_{\phi\to\infty}\frac{\int_0^\phi d\phi\,\lambda R/|\underset{\sim}{e}_3\times\underset{\sim}{b}|^2}{\int_0^\phi d\phi\, R/|\underset{\sim}{e}_3\times\underset{\sim}{b}|^2},$$

$\underset{\sim}{\kappa} = (\underset{\sim}{b}\cdot\nabla)\underset{\sim}{b}$, $R \equiv$ major radius and $B_\phi = \underset{\sim}{B}\cdot\hat{\underset{\sim}{\phi}}$. We note that $\lambda$ is proportional to the parallel current and it will be nonsecular if nested surfaces exist, a result confirmed in the interior regions of all configurations thus far investigated.

One can also construct the Mercier stability condition from this set of equations and observe whether ballooning mode localization or the Mercier condition determines stability. The last term in the $\Lambda$ equation is a stabilizing finite beta term, which offers the possibility of achieving the second stability regime.

We have investigated several typical stellarator configurations for stability. Stability properties vary considerably: e.g., Wistor-U is limited to $\beta \sim 1\%$, whereas Proto-Cleo has $V'' < 0$ and shows no stability limits with increasing beta.

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‡ This work was supported by Department of Energy Contract #DE-AC02-78-ET53082 and National Science Foundation Grant #ECS-82-06027.

# FORCE-FREE HYDROMAGNETIC EQUILIBRIA OF 3-D CONFIGURATIONS*

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The existence of force-free hydromagnetic equilibria in three dimensional toroidal configurations is examined. An expansion scheme, which was first introduced by Mercier[1] and later extended and applied by Lortz and Nührenberg[2], is utilized to investigate equilibria in terms of the distance $\rho$ from an arbitrary magnetic axis. With the introduction of the force-free constraint, equilibrium magnetic fields are calculated self-consistently. Moreover, the magnetic field components are obtainable to any desired order in $\rho$. Specific results obtained from our analysis include the following:

(1) $C_o K'(s)=0$ where $C_o$ is the magnetic field along the magnetic axis, and $K'(s)$ is the derivative of the torsion (of the magnetic axis) with respect to arc length (measured along the magnetic axis).

(2) If $K'(s)\neq 0$, it follows from (1) that the lowest order non-vanishing magnetic field component along the magnetic axis is order three in $\rho$.

(3) The harmonic content of the magnetic surfaces in this vicinity depends on whether $C_o=0$ or $K'(s)=0$ in (1).

(4) The order-n equations for the expansion coefficients have been derived. From these equations the $n^{th}$ order coefficients are obtained.

In the absence of a line current along the magnetic axis, (2) suggests that toroidal force-free equilibria with a spatial magnetic axis, such as heliacs, may be possible only if the toroidal field vanishes at the magnetic axis. Further implications of the force-free constraint will be examined, including convergence of the series expansions.

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

[1] C. Mercier, Nucl. Fusion 4, 213 (1964).
[2] D. Lortz and J. Nührenberg, Z. Naturforsh, 31a, 1277 (1976).

# ECRH INDUCED PARAMETRIC INSTABILITIES IN TOKAMAKS*

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Parametric decay processes near the upper hybrid frequency may play a significant role during the start-up of a tokamak reactor when ECRH is used for preionization. In addition, recent ECRH experiments[1] on Versator II Tokamak confirmed the presence of a three-wave interaction process at upper hybrid resonance layer. Three channels of decay of the extraordinary wave, namely, resonant decay into upper hybrid and in cyclotron waves, upper hybrid and lower hybrid waves, and nonresonant decay into Bernstein and lower hybrid waves, have been studied and thresholds for these instabilities have been calculated. The effects of linear mode conversion of the high frequency daughter wave on the development of these parametric instabilities is also evaluated and the amplification of wave intensity for the nonresonant decay is calculated.

1. F. S. McDermott, C. Bekefi, K. E. Hackett, J. S. Levine, M. Porkolab, Phys. Fluids 25, 1982.

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

# DRIFT SURFACE STUDIES OF EBT CONFIGURATIONS* WITH NONCIRCULAR MAGNETIC COILS

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ABSTRACT

We have carried out a systematic comparison of the drift surface properties of a number of noncircular magnetic coil geometries for EBT. Drift surfaces have been calculated for both a vacuum field model and a model which includes an ambipolar potential. We use the drift surface information to deduce a crude aspect ratio enhancement factor (ARE) for a range of mirror ratios at fixed midplane dimensions and a fixed major radius, R = 300 cm. For an inverse dee-shaped coil, we find that ARE ~ 1.4 in the vacuum field model but ARE ~ 1.1-1.2 when $e\phi_o \sim KT$. We find that, for both the vacuum and the potential model, Andreoletti coils can provide high ARE values but they also produce broad magnetic fields in the midplane. With $e\phi_o = KT$, we find ARE ~ 1.6 for the 6:1 height-to-width ratio Andreoletti coils, while ARE $\gtrsim$ 2 is possible for a 2:1 Andreoletti system with radially shifted coils.

*Work supported by Department of Energy, Contract DE-AC03-82ER51030.

# SIMULATION OF DRIFT-CYCLOTRON-LOSS-CONE MODES IN TANDEM MIRRORS WITH SLOSHING IONS*

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Present and future tandem mirror experiments, e.g., TMX-U and MFTF-B, are designed to be free of severe deleterious transport effects arising from drift-cyclotron-loss-cone (DCLC) instability in the end plugs. This enhanced stability is produced by the oblique injection of energetic ions (sloshing ions); the resulting ion density depression near the end plug midplane leads to a dip in the ambipolar potential, which in turn traps low-energy ions improving the microstability of the ion velocity distribution with respect to loss-cone modes. Our particle simulations of drift-cyclotron-loss-cone modes with sloshing-ion distribution functions confirm this strategy.

We adapted our stretched, hybrid-extension[1] of B. Langdon's ES1 to accommodate a depression in the positive ambipolar potential and oblique ion injection and charge exchange. DCLC fluctuations and end loss both decreased as the depression in the ambipolar potential was increased. This was traced to the enhanced trapping of warm plasma. As the injection angle decreased from $90^0$ with respect to the magnetic axis, the typical ion axial excursion increased, raising the bounce-averaged ion cyclotron frequency and leading to ion-cyclotron modes with higher frequencies. Our simulations indicated an overall reduction in DCLC fluctuation levels when sloshing ions were present. This qualitatively agrees with measurements in the TMX-U end plugs, which have revealed ion-cyclotron modes at small amplitudes with DCLC character and frequencies in the same range as in our simulations.

[1] B.I. Cohen, G.R. Smith, N. Maron, and W.M. Nevins, UCRL-88096 (Sept., 1982), to be published in Physics of Fluids.

*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.

# FINDING OF A "BREMSSTRAHLUNG CORTEX" IN ADVANCED FUEL BURNING PLASMAS*

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Ignition conditions with advanced fuels[1] such as $D\text{-}He^3$ or D-D (catalised) can be reached in high density toroidal plasmas for moderate values (below 10%) of the average $\beta$ as a result of the spontaneous formation of a bremsstrahlung cortex in the plasma column. This consists of a plasma layer at the outer edge of the plasma column where the particle thermal energy transported into it by (anomolous) electron thermal conductivity and that resulting from the reabsorption[2] of synchrotron radiation emitted from the center of the plasma column is lost by bremsstrahlung emission. In particular relatively peak temperature profiles have been obtained when analysing the evolution of the plasma column parameter by a one-dimensional transport code that include both the heating due to the relevant fusion reaction products as well as all the forms of energy loss as they are known from present day experiments. A compact toroidal configuration with magnetic fields of about 120kG elliptical cross section, and dimensions about $50 \times 70 \times 120 cm^3$ has been considered. In this case a $D\text{-}He^3$ plasma can reach steady state burning for volume average densities and temperatures around $4 \times 10^{14} cm^{-3}$ and 35KeV, respectively. Using spin polarised nuclei and assuming that no effective depolarisation process takes place, these values can be reduced significantly.

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

1. B. Coppi, Physica Scripta T2, 500 (1982)
2. S. Tamor, Report LAPS-72, SAI-023-81-189LJ (S.A.I. 1981)

# Tokamak Reactor Startup*

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The Princeton Spectral Equilibrium Code (PSEC) is used to simulate the magnetics of a tokamak reactor startup in the presence of a conducting shell. The time scale of the startup is long compared to the anomalous current penetration time so that the plasma current is distributed. The plasma is surrounded by a conducting shell which serves as a protective electromagnetic shield from disruptions. A fixed q-profile and a variable toroidal flux within the plasma are used to model internal current profile relaxation processes. Self-consistent flux linkages between external coils, eddy currents in the conducting shell, and the plasma are included. The conducting shell is modeled as a set of discrete passive coils, each of which has mutual inductance with the other current carrying elements. The flux values at these passive coils change due to finite coil resistances:

$$\frac{d}{dt}\chi_i = -r_i I_i \, ,$$

where $\chi_i = L_i I_i + \sum_{j\neq i} M_{ij} I_j - \oint \frac{d\ell}{2\pi x_b} \frac{\partial\chi(\vec{x}_b)}{\partial n} G(\vec{x}_b, \vec{x}_i)$ .

As the plasma current builds up, the plasma size will grow. It is shown that by appropriately varying the poloidal thickness of the shell, a plasma equilibrium can be maintained during the entire startup phase.

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# NEAR INTEGRABLE VACUUM MAGNETIC FIELDS IN STELLARATOR GEOMETRY

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Vacuum magnetic fields do not have a dense set of nested flux surfaces, except in the special case of helical symmetry. In general, near the magnetic axis there are good flux surfaces, while away from the axis magnetic islands overlap and field lines wander stochastically.

One can improve the vacuum flux surfaces by varying the parameters that specify a vacuum magnetic field configuration.[1] We are developing a new method for improving the field.

The new technique is based on examination of the positions and residues[2] of closed magnetic field lines. The technique is independent of the parameterization of the magnetic field. The new method (unlike the method of Ref. 1) is easily carried out to high order. Moreover, the $\int d\ell/B$ constraint on the vacuum magnetic fields can be imposed. We will present preliminary results for a simple system.

1. J. R. Cary, Phys. Rev. Lett. 49, 276 (1982).
2. J. M. Greene, J. Math. Phys. 20, 1183 (1979).

Work supported by U. S. Dept. of Energy grant no. DE-FG05-80ET-53088.

NONLINEAR MAGNETOHYDRODYNAMICS OF A THREE-DIMENSIONAL CYLINDRICAL RFP

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Recent studies have indicated that the m=1 resistive kink mode is a likely instability in the reversed-field pinch (RFP). Theoretically, such modes with high toroidal mode number ($|n| \sim 10$) have been found to have large linear growth rates when evolving in physically realistic equilibria. Nonlinear helical computations have indicated robust nonlinear behavior leading to sawtooth-like events.[1] Experimental observations on ZT-40M are not inconsistent with these calculations.[2] However, because many such modes with different helicity are simultaneously linearly unstable, three dimensional calculations are required.

In this paper we present some results of initial three-dimensional studies of this problem. We consider the case in which two modes (m=1, n=-10) and (m=1, n=-11) are present initially. We find that this nonlinear interaction leads to a fully developed turbulent spectrum in which the final state is not dominated by the original modes. The field lines are observed to become stochastic over much of the pinch during the nonlinear evolution.

We have also found that the initial equilibrium is unstable to m=1 modes with approximately equal growth rate over the range ($-25 \leqslant n \leqslant -6$), and we are studying a nonlinear case in which the entire unstable spectrum is initially excited with random phases. Preliminary results from this study will be presented.

[1] E. J. Caramana, R. A. Nebel, and D. D. Schnack, LA-UR-82-2360, to appear in Phys. Fluids (1983).

[2] R. G. Watt and R. A. Nebel, LA-UR-83-13, submitted to Phys. Fluids (1983).

# DENSITY THRESHOLD FOR PARAMETRIC INSTABILITY OF LOWER HYBRID WAVES IN A TOKAMAK*

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ABSTRACT

Lower hybrid waves of finite wavenumber in a tokamak are susceptible to parametric instabilities when a certain threshold in density and power is exceeded. At a temperature of a few hundred electron volts and higher, the channel of decay with a large growth rate is due to the nonlinear ion cyclotron damping of the heat generated by the pump and the lower hybrid sideband. Typically at $T_e$ = 600 eV, $T_i \simeq 0.6\ T_e$, $n_{0\parallel} = 4$, lower hybrid power $\simeq$ 100 kW, $\omega_0 \simeq$ 800 MHz, and $\omega_0/\omega ci = 40$, the density threshold for this process is $1.5 \times 10^{13} cm^{-3}$. This threshold is comparable (within a factor of two) to the experimentally observed value of density threshold for rf current drive in PLT, above which current cannot be driven. We computed nonlinearly the spectrum of the sideband at $\omega_0 - n\omega_{ci}$ through the nonlinear cascade of parametric interaction. The resonant decay into ion cyclotron waves is also considered and shown to have a lower density threshold and occurs preferentially near the edge.

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# Halo Plasma Physics Model for Mirror Machines with Neutral Beam Injection

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A relatively cool, low density plasma halo will fill the space between the main plasma and the first wall in fusion devices. The halo shields the main plasma from impurities and cold gas. A halo model is presented here for mirror machines utilizing neutral beam injection. The model is cylindrical and single-zone, with constant density and temperature assumed. Besides particle and power balance terms arising from neutral beam interaction with the plasma, beam dump sputtering can be important. Other, general halo features included are radial transport, ionization and charge exchange of background gas, reionization of charge-exchanged neutrals, end loss, and alpha particle heating of the halo. Line radiation is assumed to be negligible in the halo.

The model is applied to the central cells of TDF[1] and TASKA-M[2], both of which are primarily neutral beam driven. Parameters for the halos in these machines will be given. An interesting result of these calculations is that the neutral beams give very little energy to the halo since the charge exchange time for ions resulting from the interaction of neutral beam and halo is much smaller than the electron drag time. The consequent surface heat load on the first wall can be tens of watts/sq. cm.

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1. K. Thomassen, et. al., "TDF", LLNL Report UCID-19328 (1983)

2. B. Badger, private communication, (1983)

Research supported by USDOE contract 02-82-ER-54013.00 and by Kernforschungszentrum, Karlsruhe, FRG contract 130/D1/597092.

# Extensions of the Theory for Neutral-Beam Driven Impurity Flow Reversal

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Stacey and Sigmar[1)] presented a theory for NBI-driven impurity flow reversal which accounted for the effects of momentum input and drags (viscous and external) upon particle transport, taking into account the direct effects and indirect effects associated with alteration of the particle flows within the flux surface and of the radial electrostatic potential gradient. Bennett and Stacey[2)] had moderate success in applying this theory to explain the observed impurity flow reversal with co-injected beams in PLT. Burrell, Ohkawa and Wong[3)] presented an explanation of flow reversal in terms of the rapid rotation of the plasma produced by the injected beam, for trace impurity levels.

We have subsequently extended the Stacey-Sigmar formalism to consistently treat the rotation effect as well as the momentum input-drag effect by retaining the inertial term in the momentum balance for the impurity species. Particle densities and the electro-static potential are allowed to vary on the flux surfaces, and the lowest order flows and the radial potential gradient are determined from momentum balance and particle conservation. The formalism is developed in flux surface coordinates and specialized to the large aspect ratio limit to obtain some quantitative estimates.

References:

1. W.M. Stacey, Jr. and D.J. Sigmar, Nucl. Fusion, 19, 1665 (1979).

2. R.B. Bennett and W.M. Stacey, Jr., Bull. Am. Phys. Soc., 27, 1059 (1982).

3. K.H. Burnell, T. Ohkawa and K. Wong, Phys. Rev. Ltr., 47, 511 (1981).

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# MHD SIMULATION OF MARYLAND SPHEROMAK FORMATION*

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A numerical simulation of a new slow formation scheme for the Maryland spheromak will be presented. In this scheme, the poloidal field reversal and toroidal plasma currents are induced by a set of current-carrying toroidal coils, while the initial toroidal flux is induced by the external z-current, thus demonstrating that a spheromak configuration is obtainable through an appropriate combination of $\theta$- and z-discharges. Unlike the previous scheme, toroidal reversal coils are placed inside of a metal vacuum chamber. A set of 2-dimensional, compressible, resistive MHD equations are integrated in time with changing boundary conditions for the toroidal field and poloidal flux function. A fast z-current penetration was facilitated through the use of anomalous resistivity,[1] while the excitation of large amplitude Alfvèn waves, which would negate a further continuation of computation, was suppressed through the use of a viscosity coefficient larger than the classical value.[2] An optimized arrangement results in a high $\beta$ spheromak configuration after 20 $\mu$sec.

1. R. Chodura, Nucl. Fusion 15, 55 (1975).
2. S. C. Jardin and W. Park, Phys. Fluids 24, 679 (1981).

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

# EFFECTS OF TOROIDAL ROTATION AND PRESSURE ANISOTROPY ON TOKAMAK EQUILIBRIA*

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ABSTRACT

The effects on tokamak equilibria of toroidal plasma rotation and pressure anisotropy due to neutral beam injection are studied by generalizing a previous variational moment method.[1] The appropriate MHD equilibrium equations are reduced variationally to a few second order nonlinear ordinary differential equations making use of the Lagrangians

$$L_T = \sqrt{g}\ \{(B_p^2 - B_t^2)/8\pi - \tilde{p}(\psi)\ \exp[R^2\omega_t^2(\psi)/2T(\psi)]\} \quad ,$$

and

$$L_A = \sqrt{g}\ \{\sigma(B_p^2 - B_t^2)/8\pi - [p_{\parallel}(\psi,B) + p_{\perp}(\psi,B)]/2\} \quad ,$$

respectively. Here, $\omega_t(\psi)$ and $\sigma$ are the plasma toroidal rotation frequency and anisotropic factor. Specific calculations using D-III and ISX-B geometries are presented. In the anisotropic pressure case, the functional forms for the beam pressures are obtained from a model beam slowing down distribution function appropriately weighted in the perpendicular and parallel directions.

[1]Lao, L. L., et al., Phys. Fluids 24, 1431, 1981.

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

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# Ion-Beam-Driven Electrostatic Ion Cyclotron Instabilities*

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We present results of linear theory and numerical simulations on the electrostatic ion cyclotron instabilities driven by the ion beam parallel to the magnetic field. The ion beam can destabilize electrostatic ion cyclotron (EIC) waves by resonant interaction driven by the inverse ion Landau damping and nonresonant interaction arising from reactive coupling between beam and background ion cyclotron modes. Using the dispersion relation for ion beam driven EIC waves, the maximum background ion heating due to EIC instabilities may be determined from the marginal stability condition for a given drift speed.

To study plasma heating and beam slowing down numerical simulations are carried out for plasma parameters relevant to neutral injection. Here we consider a three component plasma consisting of background electrons, background ions and beam ions. Both one- and two-dimensional simulation codes are used. The results of numerical simulations show perpendicular heating of background and beam ions as well as the slowing down of the beam ions. Anomalous beam slowing down and anomalous plasma diffusion associated with the beam injection will be discussed along with the nonlinear saturation.

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# COMPRESSIONAL ALFVEN WAVES FOR HEATING AND CURRENT DRIVE

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The potential of the compressional Alfvên waves (with frequency below the ion-cyclotron frequency) to heat and generate current in thermonuclear tokamak plasmas is investigated. Special emphasis is placed on the structure of the eigenmodes for which $m > \ell$ , where $m$ is the poloidal, and $\ell$ is the toroidal mode-number. It is shown that these high-Q eigenmodes couple very strongly with an external antenna resulting in a large plasma impedance in a narrow frequency range. The energy deposition, which is due to transit-time magnetic and Landau damping, takes place preferentially in the interior hot region of the plasma. The large parallel phase velocity of these waves makes them especially suitable for driving currents. In addition, the characteristic frequencies of the waves travelling in parallel and antiparallel directions are sufficiently separated that a choice of the driving frequency will decide the propagation direction; thus obviating the difficulty of creating a travelling wave in the Alfvên-wave frequency range.

# Ripple Penetration in High and Low β, Resistively Diffused Tokamaks

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ABSTRACT

A fully 3D tokamak simulation code with classical transport has been described[1] and preliminary results (including island diagnostics) described[2]. Results are now given for the ripple penetration [definition: (max B - min B)/(average B) on a flux surface] from plasma edge to magnetic axis in its dependence on average β (from zero to 3%) and on profile. The initial profile is taken with $q_o = 1$ on axis, $q_1 = 2$ at the edge. The value $q_1$ is held fixed during diffusion. After diffusion $q_o$ rises to approximately $q_1$ at low β (the diffused profile has $q \sim$ const.); at high $\beta(\beta \gtrsim .01)$, $q_o$ dips to below one after diffusion. Increased β(to $\beta \sim .03$) slightly reduces the ripple at the plasma edge and substantially increases ($\sim$ 50%) the ripple on axis.

1. H. Grad, "Alternating Dimension Plasma Transport in Three Dimensions," in Proc. of the Fourth International Symposium on Computing Methods in Physics, Applied Sciences and Engineering, Versailles, 1979, eds. Glowinski and Lions, North-Holland Publishing Company, 1980 [MF-95, December 1979].

2. October 1981, DPP: A. Bayliss, H. Grad and J.T. Hogan, Bull. APS 26(7), p. 1002, September 1981.

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# Stability of the Hot-electron Mode in EBT*

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## ABSTRACT

A 2-1/2 dimensional relativistic, electromagnetic particle code[1] is used to study the stability of the high-frequency hot electron interchange mode[2] which is theoretically predicted to be one of the several dangerous instabilities in the Elmo Bumpy Torus. Simulation parameters are chosen such that the decoupling constant $q_o \equiv v_{dh}/\omega_{ci}\Delta$ is about unity with the density ratio $n_h/n_i$ being about 0.3, where $v_{dh}$ is the drift velocity of the hot electrons, and $\Delta$ is the half-width of the hot electron annulus. In this parameter regime, the high-frequency hot electron mode can be unstable with growth rate $\gamma \gtrsim \omega_{ci}$ according to the theory. However, our simulations show that the plasma is much more stable than the theoretical prediction. This stability is not fully accounted for by finite Larmor radius effects. A possible explanation is wave damping by the strong cross-field diffusion of the hot electrons due to their wide spread of the drift velocity; using the observed diffusion rates, $k^2D$ exceeds the theoretical growth rate.

[1]Y. Ohsawa and J. M. Dawson, UCLA Report PPG-645 (1982).

[2]R. R. Dominquez and H. L. Berk, Phys. Fluids 21, 827 (1978).

*This work was supported by U.S. Department of Energy Contract DOE DE-AM03-76SF00010 PA 26, Task VIB.

# COMBINED ELECTRON CYCLOTRON HEATING AND LOWER HYBRID CURRENT DRIVE*

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ABSTRACT

A numerical Fokker-Planck wave kinetic code has been constructed to follow the temporal evaluation of the electron distribution and the non-linearly excited plasma waves during lower hybrid current drive. The code is two-dimensional both in electron velocity space and wave number space. An algorithm which automatically adjusts the time steps to preserve numerical accuracy allows the code to study physical phenomena occurring in widely different time scales. Numerical studies using the code have verified the occurrence of relaxation oscillations during lower hybrid current drive which has been observed experimentally. Experiments have also reported the stabilization of these oscillations and improvement in current drive efficiency on application of electron cyclotron heating.[1] This is being investigated using the code and the results will be reported in this meeting.

[1]Porkolab, M., et al., Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, 1982, IAEA-CN-41/C-4.

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

# Saturated Tearing Modes in Toroidal Geometry

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A computer code has been developed to determine saturated tearing mode magnetic island widths in axisymmetric toroidal plasmas with no assumption on the aspect ratio, cross-sectional shape, or plasma pressure. The algorithm is based on a quasilinear theory of tearing modes[1] which takes into account the fact that the presence of a magnetic island flattens the background axisymmetric profiles of current and pressure. This effect removes the apparent singularities (at each mode rational surface) in the coefficents of the ordinary differential equation for each helical harmonic of the perturbed magnetic field. The width of each magnetic island is varied until the solution for the perturbed magnetic field matches boundary conditions at both the magnetic axis and the edge of the plasma. At each stage in the iteration the background axisymmetric equilibrium and its Hamada coordinates are recomputed using a variational moment solution to the Grad-Shafranov equation.[2]

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1. Glenn Bateman and R. N. Morris, "Model for Saturated Tearing Modes in Toroidal Geometry," Georgia Institute of Technology Fusion Report GTFR-31 (April, 1982).

2. L. L. Lao, S. P. Hirshman and R. M. Wieland, "Variational Moment Solutions to the Grad-Shafranov Equation," ORNL/TM-7616 (March, 1981).

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# IDEAL MARGINAL MAGNETOHYDRODYNAMICS

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Hamiltonian and quasi-Hamiltonian forms of the equations of motion for linearized zero-frequency displacements around an ideal magnetohydrodynamic equilibrium are considered using Bineau's[1,2] scalar reduction. A class of symplectic transformations is considered which leaves the Green's function invariant. In particular a transformation is found which makes the low-$\beta$ behavior more explicit. The equations are used to construct the power series (Frobenius) expansion about a rational surface. The case of indices differing by an integer is considered, in particular the low-$\beta$ limit, and it is shown that a new definition of the "big" solution avoids having to treat this limit as a special case.

1. M. Bineau Nucl. Fusion 2, 130-147 (1962).
2. R.C. Grimm, R.L. Dewar, and J. Manickam J. Comp. Phys. 1983 (to be published).

SPECTRAL-METHOD COMPUTATION OF VISCOUS, RESISTIVE MHD STABILITY*

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and M. Y. Hussaini, NASA (ICASE)

Expansions in Chebyshev polynomials are used to study the linear stability of one-dimensional MHD quasi-equilibria, in the presence of finite resistivity and viscosity. The method used is modeled on the one used by Orszag to compute critical Reynolds numbers from the Orr-Sommerfeld equation to six-figure accuracy. Two Reynolds-like numbers, $S \equiv C_A L/\eta$, $M \equiv C_A L/\nu$ ($C_A$ = Alfvén speed, L = macroscopic length, $\eta$ = magnetic diffusivity, $\nu$ = kinematic viscosity) determine the stability boundaries. The stability boundaries are determined by the combination $\sqrt{SM}$. Marginal stability curves, growth rates versus S and M, and growth rates versus $\alpha$, the parallel wave number, are displayed for finite slabs with no-slip, resistive boundary conditions at rigid, perfectly-conducting walls. A numerical result which appears general is that instability has been found to be associated with inflection points in the current profile, though the eigenfunctions are not concentrated at these points, and no analytical proof has emerged. The most unstable or least-damped eigenmode always appears with zero real frequency. The critical Reynolds-like numbers are more than two orders of magnitude smaller than their hydrodynamic counterparts. Nonlinear dynamic computations will be required to test the possibility of subcritical three-dimensional instability[1].

[1] S. A. Orszag and L. C. Kells, J. Fluid Mech. 96, 159 (1980).

* Work supported by NASA and USDOE.

# TURBULENT BEHAVIOR OF THE STRAUSS EQUATIONS*

W. H. Matthaeus and D. Montgomery

The Strauss equations of "reduced" MHD have been solved numerically by the Orszag spectral method. Viscous and resistive dissipation are included, and a strong, uniform dc magnetic field is present. The code utilizes rectangular, periodic boundary conditions with 64 x 64 x 32 spatial resolution, and runs at 4.8 seconds per time step in core on the MFE Cray-1.

Mathematically, the Strauss equations occupy a place intermediate between two-dimensional (2D) and three-dimensional (3D) MHD. Our initial approach to their turbulence properties has been through a comparison of their behavior with that of 2D MHD in similar situations, 2D turbulence being now comparatively well understood. We report here preliminary results for four problems: (1) magnetic reconnection and current filamentation for the unstable "sheet pinch"; (2) growth of magnetic energy due to purely mechanical driving of the velocity field (i.e., "dynamo" action, not seen for purely mechanical driving in 2D MHD); (3) possible inverse cascade behavior (we have not seen any yet for purely periodic boundary conditions, and believe now that if it exists, a finite net current through the system is required, and thus non-periodic boundary conditions); and (4) evolution of anisotropy in the direction of increasing mean $k_\perp/k_\parallel$, which can result in a fast dissipation of the high $k_\perp$ part of the spectrum (carried to extremes, this can invalidate the length-scale assumptions which led to the Strauss equations in the first place).

The next step of the program will utilize a spectral code which does not require periodic boundary conditions in the two directions perpendicular to the mean magnetic field. Only in the case of a net axial dc current along $\underset{\sim}{B}_0$ does it now seem likely that microscopic turbulence might lead to major tokamak disruptions.

* Work supported by USDOE and NASA. We appreciate also a helpful donation of computer time from Los Alamos National Laboratory.

# SIMULATIONS OF THE DENSITY, PHASE, AND TOROIDAL FIELD DEPENDENCE OF LOWER HYBRID CURRENT DRIVE

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We have previously described[1,2] a computer model for lower hybrid current generation that incorporates a 1-D transport code and a toroidal ray tracing code and which includes the effects of collisions, quasi-linear diffusion, and the DC electric field on the electron distribution function. This model accounts reasonably well for the magnitude and the phase and toroidal field dependence of the RF current observed in low density PLT and Alcator C lower hybrid experiments when appropriate two-sided Brambilla spectra are input at the plasma edge and individual rays are allowed to propagate and spectrally reflect from the walls/sheath until most of their energy is absorbed. Toroidal upshifts in the parallel refractive index of high phase velocity waves prior to damping play a crucial role here. If the number of reflections from the plasma edge region is arbitrarily limited to $\mathcal{O}(10)$, or if the waves are assumed to effectively lose a small fraction of their energy at each reflection, a sharp cutoff in the efficiency of current drive at $\bar{n} \simeq 7\times10^{12}$ in PLT can be obtained. A density limit also appears in simulations if wave collisional damping is considered to be enhanced by high edge $Z_{eff}$ or fluctuation phenomena.

*Work supported by U.S. Department of Energy

[1] R. Englade and P. Bonoli, Paper 2E5, Annual Controlled Fusion Theory Conference, Sant Fe, 1982.

[2] R. Englade et al, Bull. Am. Phys. Soc. 27, 1069 (1982).

# RESISTIVE BALLOONING MODES*

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ABSTRACT

In the two fluid treatment of resistive ballooning modes, four coupled ordinary differential equations are solved for the complex velocity stream function u, the perturbed electron pressure, $P_e$, the perturbed ion pressure, $P_i$, and the perturbed ion density $n_i$. If electron and ion thermal conductivity are neglected, the system of equations reduces to two coupled second order, ordinary differential equations. Applications of these equations to high-$\beta$ Doublet III equilibria will be presented. The results will be compared with results from the intermediate frequency kinetic ballooning mode theory[1] (which neglects resistivity but includes the diamagnetic drift frequencies) and the one fluid resistive ballooning mode theory[2] (which neglects the diamagnetic drift frequency).

[1]Tang, W. M., et al., Nucl. Fusion 20, 1439, 1980.
[2]Chance, M. S., et al., Plasma Physics and Controlled Thermonuclear Fusion Research (IAEA, Vienna, 1978) Vol. 1, 677.

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

# Ion Skin Depth Scaling in the Toroidal Cusp Experiment*

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ABSTRACT

We have performed computer simulations[1-2] of the Toroidal Cusp Experiment (TCX), a plasma device built and operated at the University of California, Los Angeles (UCLA). TCX is a toroidal machine with an external magnetic field provided by 48 cusps arranged in poloidal rings. A transformer generates a toroidal electric field which causes a current to flow in the plasma. Within experimental error, most of this current is ion current; the machine is characterized by high ion temperatures ($T_i \simeq 200$ eV).

The computer simulations are carried out using a 2-1/2 dimensional bounded electromagnetic particle code. The results to be presented here concentrate on three major areas.

(1) Conventional theory says that when an external low frequency electric field is applied to a plasma, the electrons do most of the shielding of the external field (skin effect) with $\delta$ = skin depth = $c/\omega_{pe}$. However, in TCX the electrons are restrained by the cusps. Simulation results confirm this and show that for an external electric field which is constant in time, the ions provide a significant amount of shielding.

(2) We study the scaling of ion collisionless skin depth versus cusp spacing. Currents in the plasma distort the cusp fields. In most cases, this distortion increases as the cusp spacing is increased, in agreement with a simple physical model. The computer results seem to indicate that operation is possible even when the cusp separation is greater than the ion skin depth.

(3) Finally, we compare some results from the bounded model with those from an unbounded (i.e., fully periodic) model. For constant external electric and magnetic fields, cusp distortion, total electric field in the interior of the plasma, and the ratio of electron current to ion currents are all smaller in the bounded model than in the unbounded one, although most qualitative results are the same. Ion shielding has only been observed in the bounded model.

References

1. J. N. Leboeuf, J. M. Dawson, S. T. Ratliff, M. Rhodes, and N. C. Luhmann, Jr., Phys. Fluids 25 (1982), 2045.
2. J. M. Dawson, J. N. Leboeuf, N. C. Luhmann, Jr., S. T. Ratliff, and M. Rhodes, Paper 1D7, 1982 Sherwood Controlled Fusion Theory Conference, Santa Fe, New Mexico, April 1982.

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# AN INTEGRAL FORMALISM FOR ELECTROMAGNETIC PERTURBATIONS IN A LOW β PLASMA. APPLICATION TO HIGH M DRIFT-TEARING MODES*

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During the last few years a number of papers[1-4] have appeared that study the stability of drift waves by solving an integral eigenvalue problem. These works, however, are limited to the case of electrostatic perturbations.

We will present a theoretical and numerical formalism for electromagnetic perturbations that takes into account finite ion gyroradius and kinetic ion effects. By using a Fourier representation for $\phi(x)$ we derive, from Ampere's law, a differential equation for a modified Green's function (in $\underline{k}$ space) that contains the effects due to magnetic perturbations. This equation is solved simultaneously with an integral equation (equivalent to the quasineutrality condition in $\underline{k}$ space) to obtain the eigenvalues and corresponding eigenfunctions.

Results on the application of this formalism to high m drift-tearing modes will be reported.

(a) Supported by Commisiôn Nacional de Energía Atómica, Buenos Aires, Argentina.
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1. R. Marchand, N. T. Gladd, and Y. C. Lee, Phys. Fluids 25, 338 (1982).
2. R. Linsker, Phys. Fluids 24, 1485 (1981).
3. L. Chen, F. J. Ke, M. J. Xu, S. T. Tsai, Y. C. Lee, T. M. Antonsen, Plasma Phys. 24 (7), 743 (1982).
4. Y. C. Lee, L. Chen, W. M. Nevins, Nucl. Fusion 20 (4), 482 (1980).

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

# AN ESTIMATE OF THE FIGURE-OF-MERIT, In/P, FOR THE TWO-STEP APPROACH TO STEADY-STATE CURRENT DRIVE IN TOKAMAKS USING ELECTRON CYCLOTRON HEATING

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## ABSTRACT

We develop a basis for estimating In/P, the conventional figure-of-merit for steady-state current drive, where P is the power dissipated in sustaining the current I in a plasma of density n. In STEP ONE of the TWO-STEP APPROACH considered here, a small fractional concentration of barely-trapped energetic electrons is created by ECH near the region of maximum magnetic intensity. In STEP TWO, some of these electrons are de-trapped by frequency-modulated ECH near the region of minimum magnetic intensity, creating a toroidally circulating density of energetic electrons that can sustain the tokamak current. It appears that In/P can exceed (2-5) x $10^{13}$ Amp/Watt$\cdot$cm$^3$, depending on the energy of electrons heated in STEP ONE and the bandwidth of the FMECH sources used in STEP TWO.

# KINETIC AND FLUID BALLOONING STABILITY IN ANISOTROPIC ION TOKAMAKS*

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We present the derivation of a kinetic ballooning mode equation for multiple anisotropic fluid ion plasmas and Maxwellian adiabatic electrons. Considering the magnetohydrodynamic (MHD) limit, we obtain a fluid ballooning mode equation similar to that derived from the Kruskal-Oberman energy principle, except that the energetic ions do not contribute to the instability driving mechanism because they drift across the destabilizing curvature region at a rate that is faster than the oscillation of the mode. A numerical example shows that the Kruskal-Oberman critical beta $\beta_c \simeq 2.65\%$ can be increased to $\beta_c \simeq 4.1\%$ when the ratio of peak energetic ion beta to peak total beta, $\beta_{h0}/\beta_0 = 0.3$. Finite Larmor radius (FLR) corrections are also evaluated.

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# UNIFIED FIELD THEORY OF DISCRETE AND COLLECTIVE GYRORESONANT WAVE-PARTICLE INTERACTION IN COMPLEX GEOMETRY*

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The Hamiltonian theory for the Vlasov distribution is extended to the Klimontovich distribution in general magnetic geometry. Suppressing magnetic perturbations (for simplicity of presentation), we derive the inhomogeneous evolution equation for the potential field, in terms of Lie-Poisson brackets on functionals of the Klimontovich distribution. The dominant part of this equation, representing free waves, is converted to a least action principle for the wave-field Lagrangian. On two-timing, the wave-action amplitude emerges as a canonical field, which interacts gyroresonantly with the oscillation-center distribution, according to a reconstituted Hamiltonian functional. The new Poisson structure is additive in the wave-action amplitude and the oscillation-center distribution; the Hamiltonian includes both resonant and ponderomotive interaction, and both discreteness and collective effects. The evolution of the wave-action amplitude thus includes Cerenkov emission, gyroresonant damping or growth, and propagation along ray trajectories. At this stage the waves are coherent, and trapping is retained. Upon phase-averaging, another Poisson structure emerges, for functionals of the wave-action density in ray phase space, of the same form as that for the oscillation-center distribution. The phase-space coordinates may be chosen to be global or local; in the latter case the incoherent interaction coefficients for spontaneous and induced emission can be manipulated into identical form. The techniques developed can now be extended to embrace spontaneous and induced scattering, and coherent or incoherent three-wave interaction.

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# RESISTIVE MODES IN REVERSED FIELD PINCHES*

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The stability and nonlinear evolution of resistive tearing and g-modes are studied in the reversed field pinch configuration using a full set of resistive MHD equations. These equations are solved numerically in cylindrical geometry using the 3-D initial value spectral-finite difference computer code CYL. The effects of compressibility and finite beta upon the linear stability and nonlinear single helicity evolution of the m=1 tearing mode are studied in detail together with the extension to multiple helicities. We also examine the linear scaling of the g-mode with S, the ratio of the resistive skin time to the Alfvén time, and with Γ, the ratio of specific heats, as well as the extension of these calculations to the nonlinear regime.

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# $\beta$- LIMITS IMPOSED BY HIGH-n BALLOONING MODES

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Some experimental results suggest that there may be a $\beta$- limit mechanism operating close to the limit predicted by ideal high-n mode calculations. Encouraged by this there have been several attempts to produce scaling laws giving the theoretical $\beta$ limits as a function of aspect ratio, elongation, triangularity and edge safety factor, $q_s$.

However there is some conflict between the various formulae produced, and predictions vary between $q_s^{-0.5}$ and $q_s^{-1.3}$. This work investigates some anomalies in the interpretation of the computed results, and attempts to clarify and reconcile the various predictions.

# Low Frequency Heating of a Resistive Doublet, Continued

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ABSTRACT

Numerical experiments are carried out in a 2D (straight) Doublet configuration[1]. In order to compare this nonlinear code with a linearized theory[2], it was necessary to operate at extremely small modulation (the current peak at the separatrix is strongly nonlinear), which required refining the accuracy of the code by a factor 1000[3]. Making use of this improved accuracy, also of certain new algorithms to improve convergence of the iteration, now allows the code to be run at much lower resistivity, approaching the adiabatic limit (with a very thin separatrix boundary layer) by an additional factor of at least 100. These new results should have important implications with regard to magnetic reconnection.

1. Grad, H., P. N. Hu, D. C. Stevens, E. Turkel, "Classical Plasma Diffusion," IAEA, 1977, Vol. II, 355-367.

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

3. November 1982, DPP: M. Kress and H. Grad, Bull. APS 27(8), Part II, p. 972, October 1982.

# DEGRADATION OF ELECTRON ENERGY CONFINEMENT PROPERTIES IN THE PRESENCE OF AUXILIARY HEATING

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We have refined the formulation[1,2] of a diffusion coefficient for electron thermal energy transport in plasmas with significant auxiliary heating. In particular we have used the observation that for an ohmically heated plasma (in the limit of classical resistivity), the electron temperature $T_e$ will scale as $J_{||}^{2/3}$, where $J_{||}$ is the axial plasma current density. This is then extended to a plasma with significant "injected" heating relative to the ohmic heating, so that $T_e \sim (S_e)^{2/3}$, where $S_e$ is the resulting power flow to the electrons due to the auxiliary source. As in previous work[1,2] it is assumed that the "optimal" profile for the auxiliary heating source is close to the ohmic heating profile and the electron energy confinement time degrades for any departure in the profile of the auxiliary source from the ohmic heating profile. Theoretical predictions of electron thermal diffusion coefficient and loop voltage will be compared with results from the PLT and ISX-B neutral beam injection experiments. In addition, the auxiliary diffusion coefficient is applied to numerical simulations[3] of the high power ($P_{RF} \simeq$ 1MW) lower hybrid heating experiment currently being done on the Alcator C device.

1. B. Coppi, Comments on Plasma Physics and Controlled Fusion 7, 1 (1982).
2. P.T. Bonoli, B. Coppi, et al., Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research (Baltimore, USA, 1982) IAEA-CN-41/W-2.
3. R. Englade, and P.T. Bonoli, Proceedings of the Sherwood Controlled Fusion Theory Conference (Santa Fe, New Mexico, 1982) Paper 2E5.

# REVERSED FIELD PLASMA CONFIGURATIONS IN THE UPPER ATMOSPHERE

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Intense auroras may on occasion produce magnetic field changes, $\Delta B_0/B_0$, up to about 5 percent. At least two types of events in the upper atmosphere have apparently generated reversed field plasma configurations in which $\Delta B_0/B_0$ exceeded unity[1]. The magnetic field due to a current ring (magnetic dipole) is given approximately by $\Delta B_R = \Delta B_0(a/R)^3(1 + 3\cos^2\theta)^{1/2}/2$, where $\Delta B_R$ is the magnetic field change measured at R, $\Delta B_0$ is the dipole magnetic field at the current loop center, a is the minor radius of the current loop, R is the distance to the point of measurement, and $\theta$ is the angle between R and the normal to the current ring.

Type I: On the night of January 25–26, 1938, at least two giant red spots were observed in the upper atmosphere during a spectacular aurora. The height above the earth was about 500 km and the radius was ~150 km for the red spot. Barlow reported a $2^0$ extraordinary sweep of the magnetic needle east to west and later a 3% decrease in the horizontal component of the earth's magnetic field (this latter could correspond to the formation of a second, smaller counter ring current embedded in the earlier reversed field region of an initial ring current). The red spots were not observed until after the most active magnetic period because of cloud cover in the early stages when the magnetic activity was most intense, so there is not a unique correlation between the magnetic activity and the most intense auroral features with the giant red spots. Taking values of $a \leqslant 150$ km, $R \geqslant 500$ km, $\Delta B_R \geqslant 0.01$ gauss, and $\theta = 90^0$ ($\theta \neq 90^0$ would greatly increase R/a), one obtains $\Delta B_0 \geqslant 0.8$ gauss. This gives a field reversal factor (taking $B_0 = 0.5$ gauss) of $\Delta B_0/B_0 \geqslant 1.6$.

Type II: Following the TEAK megaton explosion at 48 miles altitude on August 1, 1958, a brilliant fireball lifted and expanded to about 100 miles radius and a red glow extended out to about 300 miles radius after a time lapse of 6 minutes. The STARFISH PRIME 1.4 megaton detonation at 248 miles altitude in 1962 lit the sky all the way to Hawaii and Australia. It produced a positive perturbation of the earth's magnetic field of about 2 or more gamma (1 gamma = $10^{-5}$ gauss) for several minutes at LaHabra, California, (about 4000 miles from ground zero at Johnston Island). The magnetic perturbation due to the TEAK explosion was of order 15 gamma 6 minutes after the shot (later $\Delta B_R$ increased to about 50 gamma) as measured at Fanning Island ($\theta \cong 45^0$, R = 1200 miles); the field reversal factor for the fireball ($a \cong 50$ miles) is of order 5. The STARFISH PRIME explosion gives a similar field reversal factor using $a \cong 100$ miles, $R \cong 4000$ miles, $\theta \cong 90^0$.

Should a giant, ball-lightning-like reversed field configuration with a negative core be developed in the lower atmosphere, ExB drifts would lead to collisional energies proportional to the *masses* of the ions and might lead to ignition of the atmosphere with disastrous consequences for mankind. Studies should also incorporate: nucleus excitation level effects; nuclear polarization effects; gamma-driven burn enhancement; and the Ion-Layer, Electron-core configuration.

[1] J. Rand McNally, Jr., "Was this the "Great Sign" prophesied at Fatima?", Bull. Am. Phys. Soc. 27, 1026 (1982).

# SCATTERING AND STOCHASTICITY OF ELECTRONS INTERACTING WITH COHERENT WAVEPACKETS

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The momentum transfer and diffusion of electrons periodically interacting with a coherent longitudinal wavepacket is considered [1,2,3]. Such a problem arises, for example, in lower-hybrid current drive. We establish the stochastic threshold, the stochastic region $\Delta v_{stoch}$ in velocity space, the associated momentum transfer j, and the diffusion coefficient D. We concentrate principally on the weak-field regime, $\tau_{ac} < \tau_b$, but some strong-field results are also discussed. We numerically solve the equation $\ddot{x} = \alpha \exp(-\beta x^2) \cos(x-t)$, where $\alpha = \omega_b^2$, $\ell$ is the effective torus length, $\beta = 1/d^2$ with 2d the interaction region width, and $k = \omega = 1$. We monitor the averages $\langle v-v_o \rangle \simeq j$, and $\langle \delta v^2 \rangle = \langle v^2 \rangle - \langle v \rangle^2$ for a group of particles all launched at $v = v_o$ but distinguished by different initial positions. An increase in $\langle v \rangle$ and $\langle \delta v^2 \rangle$ is positively correlated with the onset of stochasticity. We find that $j \simeq \Delta v_{stoch}$. The diffusion coefficient $D \equiv \langle \delta v^2 \rangle / 2t$ lies below the quasilinear value and does not scale as $\alpha^2$. The discrepancy disappears if only overlapping modes of the Fourier spectrum are included in the rms field, and the autocorrelation time taken as $\pi/\Delta v_{stoch}$. In the trapping regime, $\tau_b < \tau_{ac}$, momentum transfer and stochasticity persist owing to non-adabatic transitions between trapped and untrapped orbits as the particle traverses the wavepacket. The scattering in v-space, however, loses diffusive character owing to strong perturbations.

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1. T.H. Stix, Proc. of the Joint Varenna-Grenoble Int. Symp. on Heating in Toroidal Plasmas, 1978, Vol. 2, p. 363.

2. K. Matsuda, Reports GA-A16303, 1980; GA-A15816, 1981.

3. V. Fuchs, V. Krapchev, A. Ram, and A. Bers, 1983 Topical Conference on Radio-Frequency Plasma Heating.

# THE RENORMALIZATION GROUP APPLIED TO NONLINEAR MAPPING*

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It has been found recently that many classical dynamic systems exhibit scaling behavior and universality near turbulent transition. In fact, this behavior could be modeled by simple nonlinear mappings. On the other hand, there has been tremendous progress in understanding phase transitions which also exhibit scaling and universality based on renormalization group methods developed in the quantum field theory.[1] In the present work we apply the renormalization method of phase transition theory to nonlinear mapping. First we substitute the deterministic description by a probabilistic one, introducing the "partition function". Second we find correspondence between such physical quantities as correlation length in phase transitions and correlation time for mapping. The objective of our study is to be able to calculate critical exponents near turbulent transition.

*This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-78ET-51013.

[1] K.G. Wilson and J. Kogut, Physics Report 12c, 76 (1974).

# POINT MODEL CALCULATION OF MFTF-B*

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The equilibrium parameters for the axicell MFTF-B have been calculated using point models. We describe the present models, highlighting the recent changes in the formulation and the modeling changes currently in progress. We discuss the improvements in the models for calculating the microwave power that produces the hot and warm electrons in the thermal barrier and potential peak regions of the anchor and also discuss the effects of model changes on the sloshing neutral beam and high energy pump beam requirements in the anchor. In addition, the results of a Fokker-Planck study of the ion confinement in the central cell of MFTF-B are presented and their impact on the point models is discussed. The results of a representative calculation are presented.

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# Initial Startup of a Tandem Mirror Reactor*

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When attempting to start up a TMR, various constraints on temperature, densities, applied power, pumping requirements, etc., will limit the possible operational paths. This paper proposes a possible TMR startup scenario together with the range of plasma parameters that must be achieved. The scenario and constraints are obtained by adhering to general MHD and microstability guidelines while solving the particle and power balance equations analytically for the dominate terms. This is done for the early phases of startup, prior to the establishment of the electrostatic plug potential. We propose a low density startup by initiating the plasma with ECRH on the background gas in the plug region to satisfy MHD constraints. Next, ICRF in the center cell produces a warm, low density collisionless plasma which will reduce the thermal barrier filling rate and yield higher confinement times. Simultaneously, drift orbit pumping in the transition region initiates the thermal barrier formation. The particle and power balance equations yield bounds for the neutral gas density, hot electron density, center cell ion density and drift orbit pumping. These are expressed as functions of electron and ion temperatures as well as machine dependent quantities such as RF power, mirror ratios, central cell and plug effective lengths, and the axial variation of the magnetic field. The latter "geometric" quantities provide scaling guidelines for reactor designs.

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# AMBIPOLAR POTENTIAL IN TOKAMAK PLASMA WITH TIME-DEPENDENT MAGNETIC FLUCTUATIONS*

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ABSTRACT

Magnetic field stochasticity in tokamaks is a possible explanation of observed anomalously large electron energy transport. The rapid particle transport of electrons as compared with ions gives rise to a positive ambipolar potential (positive radial electric field), assuming static magnetic fluctuations.[1] If the magnetic turbulence is not static, then the radial electric field $E_r'$ is positive in a frame moving with the fluctuations. From QL theory, we find the relationship

$$E_r' = E_r + \left(\langle B\rangle/c\right) \sum_{\vec{k}} D_{st\,\vec{k}} \left(\omega_{\vec{k}}/k_\theta\right)/\left(\sum_{\vec{k}} D_{st\,\vec{k}}\right) \quad ,$$

where $E_r$ is the radial electric field calculated in the rest frame of the tokamak, $k_\theta$ is the wave vector perpendicular to the static magnetic field, $D_{st\,\vec{k}} = |v_\parallel|\ |\delta B_{\vec{k}}/\langle B\rangle|^2 \cdot R[k_\parallel v_\parallel - (ck_\theta E_r/\langle B\rangle) - \omega - i\nu]$, and $R[\ldots]$ is a resonance function. In the steady state, $E_r' \approx -T/e\ \partial(nT^{1/2})/\partial r$. Note that the electric field $E_r$ in the rest frame may be either positive or negative, depending on the fluctuation phase velocities. Implications with regard to particle transport and ambipolarity will be discussed.

[1]Harvey, R. W., et al., Phys. Rev. Lett. 47, 102, 1981.

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

# LIMITS ON THE CONSTRUCTION OF NUMERICAL EQUILIBRIA USING THE STELLARATOR EXPANSION TECHNIQUE*

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Calculations of equlibria in Stellarator configurations have been carried out with a variety of 3D computer codes.[1] An important function of these calculations is to determine, for coil configurations of interest, the highest $\beta$ for which an equilibrium can be found. Alternatively, the Stellarator expansion[2] can be used. With this approximation, the problem is reduced to a 2D one. This fast technique can be used to scan large regions of parameter space, with critical cases being confirmed by one of the 3D codes.

These are all constructive techniques. When the calculations confirm that an equilibrium exists, they describe it. However, when the codes do not find an equilibrium, one cannot tell whether there is no solution or just that the construction technique has failed to find solutions which exist.

Here, we report on recent efforts to improve the numerical techniques involved in obtaining axisymmetric equilibria using the Stellarator expansion. The vacuum field plays an important role. We discuss several improvements in the representation for the vacuum field, starting from a Cartesian representation.

For the equilibrium calculation, itself, we have traditionally used a Cartesian representation. Here, we propose an inverse method in which, given the desired Jacobian, one solves for the spectral representation of the coordinates

$$R = \sum_m (R_m^c(\rho)\cos m\Theta + R_m^s(\rho)\sin m\Theta)$$

$$Z = \sum_m (Z_m^s(\rho)\sin m\Theta + Z_m^c(\rho)\cos m\Theta) \quad ,$$

where R, Z are Cartesian, $\rho$ is a Flux coordinate, and $\Theta$ is a generalized poloidal angle. This approach is desirable because it can produce an accurate solution which is in a convenient form for input to a stability calculation using flux coordinates.

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†Fusion Energy Division.

[1]O. Betancourt, P. Garabedian, Bull. Am. Phys. Soc. 27, 1023 (1982); R. Chodura, A. Schluter, J. Comp. Phys. 41, 68 (1981); T. C. Hender, B. A. Carreras, V. E. Lynch, Bull. Am. Phys. Soc. 27, 1020 (1982).

[2]J. M. Greene, J. L. Johnson, Phys. Fluids 4, 875 (1961).

[3]J. A. Holmes et al., J. Comp. Phys. 36, 36 (1980).

# Internal Kinks and Fishbones*

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Fishbones are soft x ray and Mirnov oscillations found during high neutral beam power PDX discharges. We show that the internal kink mode combined with enhanced beam loss, can account for the observations.

The internal kink is unstable for beta above a certain threshold, for $q_o$ in a range below 1. Using particular profiles and the high beta tokamak ordering code HIB, we find a critical beta poloidal = 0.2 × aspect ratio, for $1 > q > 0.7$. Experimentally, beta increases in time while q decreases. When the parameters are in the unstable range, nonlinear computations show the plasma center "bounces" around inside the q = 1 surface. Beam heating and a mode amplitude-dependent loss process are modelled in the pressure equation. The bouncing is sufficiently fast so that reconnection does not occur. When the internal link is stable (e.g. $q < 0.7$) the mode is resistive and causes reconnection, observed as a sawtooth. This raises q back to 1 and the process starts over, as q decreases.

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# Fast Ion Thermalization and Confinement in TF-Rippled Tokamak Reactors*

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A Monte-Carlo, Fokker-Planck method is being used to examine fast ion thermalization and losses, via a DEposition, Slowing-down, ORBit code (DESORB). The code was written by R. H. Fowler [1] based on a Monte-Carlo technique developed by R. J. Goldston [2]. The Fowler code has been modified to follow non-hydrogenic fusion products in a tokamak with TF ripple. The magnetic field model uses a D-shaped high-β, single-poloidal-null, INTOR equilibrium. The ripple field is based on realistic ripple data assuming the D-shaped TF coil design for INTOR, having a finite coil cross section with a uniform current density. The net $\vec{B}$-field is then the sum of the equilibrium plus TF fields minus the 1/R-toroidal component, and is both divergence free (TF and equilibrium components) and curl free (TF components). The plasma model assumes a steady-state, marginally-ignited INTOR plasma with transport-consistent profiles for temperature and density. The model also includes the 0.5m upward offset of the magnetic axis from the mid-plane of the TF coils, due to the single-poloidal-null in the equilibrium. The 3.5-MeV alphas are launched isotropically in velocity and randomly within one toroidal sector since there is symmetry among the N(=12 in INTOR) toroidal sectors. The number of particles born as a function of radial position is consistent with the cumulative probability distribution of the alpha source. The poloidal birth position is random in poloidal angle, allowing for finite-β effects in the D-shaped plasma. The fast ion thermalization model follows the particle guiding centers through the rippled plasma field. Pitch-angle scattering, slowing-down on ions and electrons, speed diffusion and toroidal electric field effects are included. Particles are considered lost when they hit the D-shaped wall.

In the case of INTOR with about 1% peak-to-average ripple at the plasma edge, the results of 1000-particle simulations show a 7% particle loss with a 2.4% and 2.9% energy losses for $Z_{eff} = 1$ and 1.5, respectively. The losses are strongly peaked between the TF coils, as well as very peaked in poloidal angle on the outboard wall. The peak loads are 0.34 and 0.23 $MW/m^2$ for $Z_{eff} = 1$ and 1.5, respectively. These results suggest that fusion alpha confinement is not seriously impaired by the presence of toroidal field ripple in INTOR-like tokamaks.

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[1] R. H. Fowler and J. A. Rome, ORNL/TM-7774 (1981)

[2] R. J. Goldston et al., J. Comp. Phys. 43 (1981) 61

# Evaluation of Mercier's Criterion in the WVII-AS Stellarator

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The evaluation of the MHD stability of 3D computational equilibria was hitherto performed by analyzing gross unstable modes [1] which turned out to be a rather cumbersome tool. Comparison [2] of unstable modes and Mercier instability in the case of pressure driven modes in helically symmetric eqiulibria proved the relevance of Mercier's criterion. Therefore, its evaluation in 3D computational equilibria modeling stellarators without net toroidal current is an adequate way to facilitate the search for stable configurations. An evaluation of Mercier's criterion, which is a prerequisite for the ballooning stability analysis, has been obtained with a particular 3D code as basis [3]. Test cases have been

(i) the cylindrical screw pinch (Suydam's criterion);

(ii) the straight $\ell = 2$ stellarator whose unstable behavior was demonstrated at low $\beta$ ;

(iii) a toroidal $\ell = 2$ stellarator with twist number $t_0 = 0.54$, aspect ratio A = 20, number of periods 5, $\beta_0 = 0.02$ which is unstable;

(iv) the WVII-AS stellarator; preliminary results seem to indicate a stability boundary of about $\langle\beta\rangle \simeq 1$ %.

In all cases convergence studies with respect to the mesh size have been performed and showed that the method of evaluation chosen (which exploits the well known fact that $\vec{j}$ can be obtained without using $\vec{j} = \nabla\times\vec{B}$ locally) converges acceptably and allows a prediction of the stability behavior at relatively coarse grids.

[1] F. Bauer, O. Betancourt, P. Garabedian, Phys. Fluids 24 (1981) 48.

[2] R. Gruber, F. Troyon, D. Berger, L. C. Bernard, S. Rousset, R. Schreiber, W. Kerner, W. Schneider, K. V. Roberts, Comput. Phys. Commun. 21 (1981) 323.

[3] F. Bauer, O. Betancourt, P. Garabedian, A Computational Method in Plasma Physics, Springer-Verlag, New York, 1978 (Springer Series in Computational Physics).

# TEARING MODES AND THE PARALLEL ELECTRIC FIELD BOUNDARY CONDITION

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Conventional tearing mode analysis[1] relies on the separation of the problem into: 1) an inner region near the mode rational surface where non-ideal MHD effects become important and the fields vary rapidly spatially; and 2) an exterior region where ideal MHD effects dominate and the fields vary slowly. The key to this separation is the fact that $E_\parallel \to 0$ (small compared to parallel vector potential) in the exterior region. This is used as a boundary condition on the inner layer eigenmode equations.

The validity of the $E_\parallel \to 0$ boundary condition is re-examined and found to be quite delicate in the case of drift-tearing modes at long mean free path. The exterior behavior of $E_\parallel$ depends upon the mode number, several ion-kinetic effects, and parity breaking of the equilibrium distribution function. Appropriate boundary conditions for the eigenmode equations are obtained.

Reference

1. H. P. Furth, J. Killeen, and M. N. Rosenbluth, Phys. Fluids 6, 459 (1963).

# MAGNETIC FLUCTUATIONS IN HIGH-β CIRCULAR AND NONCIRCULAR TOKAMAK DISCHARGES*

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## ABSTRACT

Magnetic fluctuations resulting from the nonlinear evolution of finite-β kink-tearing modes are calculated for high-β circular and noncircular tokamak discharges. Linear growth rate $\gamma$ and magnetic fluctuations $\tilde{B}$ become independent of both plasma resistivity and viscosity at high-β. The nonlinear evolution has fast and slow growth phases. A useful quantity is $\tilde{B}$ calculated at the transition time from fast to slow growth. The calculated β-limit in terms of an allowable level of $\tilde{B}$ shows some similarity to the experimental β-limit of some of the tokamak discharges; e.g., high $\tilde{B}$ prevents tokamak discharges from going into a high-β region. $\tilde{B}$ as well as $\gamma$ has strong dependence on $q_\ell$ and $q_0$. Substantial reduction in $\tilde{B}$ can be achieved by the use of small $q_0$ especially at high-$q_\ell$ and at high-β. The effects of broader q or pressure profiles and noncircularity are stabilizing. A higher ratio of $q_\ell/q_0$ is also stabilizing. Analyses of some of the high-β noncircular discharges in Doublet III also will be presented.

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# Confinement Effects of Electron Heating on the Thermal Barrier of a Tandem Mirror*

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The thermal barrier[1] of a tandem mirror reduces the energy transfer between the plug and central cell electrons. Selective heating of plug electrons becomes possible and modifies the plug potential confining the central cell ions.[2] Moreover, heating of the barrier electrons has been proposed,[1] with the intended result being an increase in the depth of the barrier potential. In order to assess the possible benefit of applying ECRH in the thermal barrier region, a simple thermal barrier model appropriate to present tandem mirror experiments is considered. The collisional fluxes of the hot barrier electrons diffusing into the central cell and plug, the warm electrons escaping from the plug, and cooler central cell electrons passing over the thermal barrier and becoming trapped, are evaluated in order to estimate the effect of the hot barrier electrons on the ion plugging potential. The relations for electron flux conservation in velocity space then determine the plug and barrier potentials and allow a comparison between varying amounts of barrier electron heating.

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*Work supported by U. S. Department of Energy Contract No. DE-AC03-ET53057 with Science Applications, Inc.

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

[2]P. J. Catto and R. Carrera, SAI-254-82-242-LJ/PRI-48 (1982).

# COLLISIONAL BOUNDARY LAYER EFFECTS ON THE THERMAL BARRIER ION TRAPPING RATE OF A TANDEM MIRROR*

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An analysis of the particle distribution function in a tandem mirror correct to order $\nu_s/\omega_b$ ($\nu_s$ = collision frequency, $\omega_b$ = bounce frequency)[1] results in an expression for the ion trapping rate in the thermal barrier region which is singular in the strong pumping limit. However, small-angle Coulomb collisions between the thermal barrier ions smooth out the steep gradient that the distribution function has at the boundary contour separating trapped from untrapped particles in the thermal barrier velocity space and which is responsible for the singular behavior of the ion trapping rate for strong pumping. In order to remove this singularity an appropriate Fokker-Planck equation needs to be solved for time scales $\nu_s/(\Delta\zeta)^2 \sim \nu_{cx} \sim \omega_b$ ($\zeta = v_\parallel/v$, $\nu_{cx}$ = charge exchange pumping rate) within a region around the boundary contour in velocity space and for the various regions of the device. In the limit of a long central cell a diffusion type equation of the form $\frac{\partial f}{\partial z} = \frac{\partial^2 f}{\partial x^2} - \gamma f$, ($\gamma = \nu_{cx}/\omega_b$) with mixed boundary conditions is obtained. This problem can be reduced to a Wiener Hopf equation along a boundary line in phase space. The solution to this boundary layer problem has a continuous derivative at the boundary contour of velocity space which is bounce averaged to obtain the ion trapping rate.

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* Work supported by the U.S. Department of Energy under contract DE-AC02-80ER53104.

1 R. Carrera and J.D. Callen, UWFDM-466 (1982), (to be published in Nuclear Fusion).

# DETERMINATION OF A VALUE FOR THE ANOMALOUS ELECTRON THERMAL CONDUCTIVITY

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The expression for the anomalous electron thermal conductivity in a toroidal plasma,

$$D_{th}^{eo}(r) = 5.35\times10^{13}\ \varepsilon_c \frac{a}{r} \frac{B_p}{n^{4/5}} \frac{\lambda_{ei}^{2/5}}{T_e A_i^{1/5}}\ \mathrm{cm}^2/\mathrm{s}\ ,$$

where $B_p(G)$, $T_e(eV)$, $n(cm^{-3})$, $\lambda_{ei}$ is the Coulomb logarithm, and $A_i$ the atomic mass number, has been shown [1] to reproduce the dependences of the experimental data. However, the value of the universal machine-independent constant $\varepsilon_c$ determined by calculating global confinement times [2] is somewhat higher than that determined by matching experimental profiles using a transport code. This study uses a transport code that includes the effects of sawtooth oscillations to determine values of $\varepsilon_c$ for several devices, over a range of q. For Alcator A, values of $\varepsilon_c$ from 0.21 - 0.23 reproduce the measured temperature low q discharges, while $\varepsilon_c = 0.26 - 0.28$ for high q discharges. These ranges overlap if the experimental uncertainty in the temperature is taken into account. Low q discharges from FT fall within the same low q range. Finite aspect ratio corrections to the ion neoclassical thermal conductivity will lower these values.

1. B. Coppi and E. Mazzucato, Phys. Lett. 71A, 337 (1979).

2. P.T. Bonoli, et al., Proc. of 9th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore (1982).

# TANDEM MIRROR EXPERIMENTS: RESULTS AND COMPARISON WITH THEORY

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Tandem mirror experiments have made considerable progress in stably confining and heating plasmas. In this paper many of the important results are reviewed, together with their theoretical bases. Attention is given both to areas of agreement and to those areas of incomplete theoretical understanding. The topics discussed include equilibrium and confinement, e.g., heating and fueling, spatial distribution of electron and ion parameters, and axial and radial loss mechanisms. Results on plasma stability will be discussed for MHD modes, low-frequency (trapped-particle) modes, and ion and electron microstability.

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Modeling of ICRF Heating of a Tokamak Plasma*

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A model for wave propagation and absorption in the ion cyclotron range of frequencies (ICRF) has been constructed and fitted into the one-dimensional BALDUR transport code. The wave propagation is handled by ray tracing techniques. Wave absorption is calculated by using the Fokker-Planck equation and quasi-linear diffusion. The wave propagation and damping profiles are evolved in time according to the plasma evolution. A simulation of PLT minority ICRF heating with a comparison to experiment is given.

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A Fokker-Planck Equation for Spin-Polarized Particles*

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Recent work[1] has indicated that spin polarized particles may stay polarized in fusion plasmas for times well in excess of the reaction time. By controlling the polarization of the reacting plasma the direction of alpha particle emission and the reaction rate can be controlled. In order to calculate polarization as a function of time for arbitrary initial polarization and plasma condition, the distribution function has been generalized to include spin as well as space and velocity variables and a Fokker-Planck equation derived to describe its time evolution. The collision term includes spin orbit, spin-spin, and quadrupole interactions. Equations for spin 1/2 and spin 1 nucleons are given and the generalization to higher spin outlined. Taking moments over spin space reduces the equation. The reaction rates are given in terms of these moments. The guiding center approximation is given, the quasilinear depolarization by waves and the depolarization by collisions in an inhomogeneous magnetic field are calculated. These results recover in more generality the results of ref. (1). No new depolarization mechanisms have been found. Throughout, an attempt has been made to provide all the equations necessary to calculate nuclear reaction rates and emission distributions from the solution to the Fokker-Planck or moment equations thereby removing the need for further reference to quantum mechanics.

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

†Harkness Fellow

[1] R.M. Kulsrud, H.P. Furth, E.J. Valeo, and M. Goldhaber, Phys. Rev. Lett. 49, 1248 (1982).

# INSTABILITY OF FUSING PLASMAS AND RELEVANT SPIN-DEPOLARIZATION PROCESS*

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In a plasma that is composed of a mixture of fusing nuclei (e.g. D-T or D-$He^3$) a new unstable mode with frequency intermediate between the cyclotron frequencies of the fusing nuclei (e.g. D-T or D-$He^3$) is shown to be excited under rather general conditions. The relevant driving factor is the anisotropy of the fusion reaction product (e.g. 3.5MeV $\alpha$-particles) distribution that is characteristic of the case of fusion with spin-polarized nuclei[1], or that, in the case of unpolarized fuels, can be the result of preferential losses of a significant portion of the fusion reaction product orbits. These modes are electromagnetic, in that they involve a significant perturbation of the magnetic field and do not suffer appreciable electron Landau damping as they have a relatively small fluctuating electric field in the direction of the equilibrium magnetic field.

We point out that the deuteron spin precession frequency equals 0.86 times its cyclotron frequency. Since the magnetic field of a realistic confinement configuration is inhomogeneous, the considered mode frequency matches the deuteron spin precession on a surface that is very close to the one where the mode is excited. Hence we evaluate, as a function of the mode amplitude, the probability for spin-flip transition. Then on the basis of the flow of particles through the resonant region we evaluate the rate of spin depolarization. We find that this can be considerably faster than the fusion reaction rate, even for relatively low values of the considered mode amplitude.

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

1. R.M. Kulsrud et al., Phys. Rev. Letters 49, 1248 (1982)

# ENERGETIC PARTICLE STABILIZATION OF BALLOONING MODES IN TOKAMAKS

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The presence of an anisotropic, highly energetic ion (or electron) population in a tokamak device is found to allow direct access at constant shear into the regime of second ballooning stability[1], after which the energetic population is no longer required.

We investigated the situation in which an anisotropic population of hot ions is mirror-trapped on the outer side of the torus. The temperature of the hot ions is such that their magnetic drift frequency is taken to be much larger than the MHD growth rate. A large-aspect-ratio model equilibrium for which the pressure gradient is localized in a thin layer[2] was adopted for simplicity. The linear stability of high-mode-number modes was obtained by numerical solution of a ballooning integro-differential equation that was derived from a lower bound to the low-frequency kinetic energy principle.[3,4] Although this procedure underestimates stability, the results nevertheless indicate that hot ions trapped, for example, between $\theta = \pm\pi/4$ are able to stabilize ballooning for shear values up to $rq/q \cong 0.9$ and for beta values beyond the second stability limit ($\beta_T \cong r/R$). The effect of hot ion finite Larmor radius is found to improve the predicted stability even more.

We are also investigating stabilization of heliacs by the same process, as suggested by Furth and Boozer.[5] The effects of "sloshing" ions and FLR will be discussed. Finally, we note that when the drift frequency is not high enough to completely decouple the energetic species, there is a tendency for the MHD mode to acquire a real frequency close to the drift frequency of the energetic species, perhaps correlating with "fishbone" observations.

References

1. B. Coppi, A. Ferreira, J. Mark, and J. Ramos, Nucl. Fusion 19, 715 (1979).
2. J. M. Greene and M. S. Chance, Nucl. Fusion 21, 453 (1981).
3. J. W. Van Dam, M. N. Rosenbluth, and Y. C. Lee, Phys. Fluids 25, 1349 (1982).
4. T. M. Antonsen and Y. C. Lee, Phys. Fluids 25, 132 (1982).
5. H. P. Furth and A. H. Boozer, memorandum (1982).

# Stability of Bean-Shaped Tokamak Equilibria Against Localized MHD Modes*

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We are currently investigating the stability properties of tokamaks which are characterized by having their surfaces concave towards the plasma at the inner major radius side, i.e. a bean-shaped cross-section. The resultant distribution of the poloidal flux surfaces provided by the indentation is seen to have a strong stabilizing effect against localized ballooning modes, a phenomenon which was previously observed by Miller and Moore[1]. A quantity which appears to play an important role is the local shear, S[2]. In a more conventionally shaped tokamak, S usually has vanishing points in the region of bad curvature and this renders the plasma susceptible to ballooning. However, with the bean shape the vanishing points of S can be expelled away from the bad curvature region, thus making the local interchange of field lines more difficult there. We have in fact demonstrated that with a moderate indentation, accessibility to the second region of stability against ballooning modes can be achieved. This paper addresses mainly the stability against localized modes and presents some of the equilibrium properties. Other papers[3,4], deal with the internal kinks and free boundary modes and also with the field coil designs for an actual experiment.

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

[1] R. C. Miller and R. W. Moore, Phys. Rev. Lett. 43, 765 (1979).
[2] J. M. Greene and M. S. Chance, Nucl. Fusion 21, 453 (1981).
[3] J. Manickam, et al., this conference.
[4] S. L. Mendelsohn, et al., this conference.

# A KINETIC MODEL OF PLASMA FLOW TO DIVERTORS AND LIMITERS*

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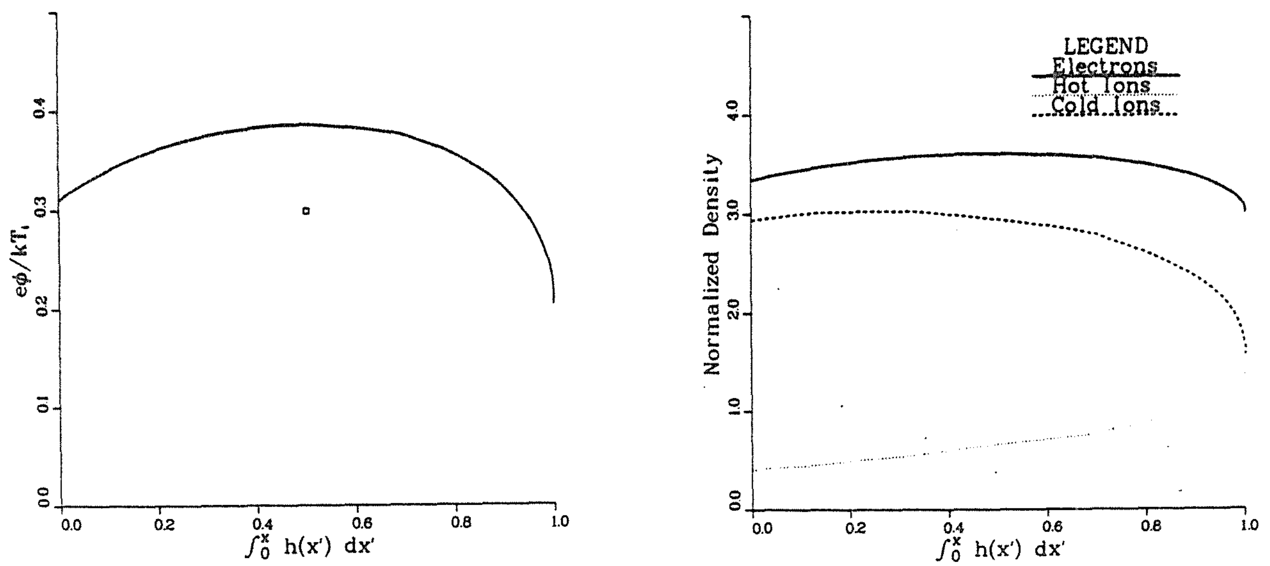
In divertors and pumped limiters, plasma flows along magnetic field lines from the scrape-off layer to a material wall where it is neutralized. The neutrals refluxing from the wall will undergo ionization and charge exchange, producing cold ions. These cold ions will cause an increase in the electric potential over that which would otherwise exist in the region in which the ionization and charge exchange takes place. Depending on the location of the peak in the potential, the cold ions will flow down the potential gradient either towards the scrape-off zone or the wall.




Potential and density profiles in a divertor or limiter as a function of the integrated normalized neutral ionization and charge exchange distribution function with the potential peaking in the center of the integrated distribution.

This problem has been examined using a largely analytical, kinetic model. Both the case of a uniform magnetic field and the case of a magnetic field possessing a constriction (as in a bundle divertor) are presented. The effects of charge exchange are discussed.

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# Plasma Transport in High Density Divertors*

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Fluid equations in toroidal flux coordinates are derived for the subsonic flows characteristic of axisymmetric tokamak divertors with high plasma density. Radial particle flows are found to be dominated by Pfirsch-Schlüter flows. Strong ion-electron temperature equilibration leads to cancellation of neoclassical radial ion and electron conduction. The scrapeoff thickness can be estimated from the radial particle flow and is found to be 3 cm for the Doublet-III expanded boundary divertor, in agreement with experimental observations. Numerical solutions of the fluid equations are discussed.

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# Monte-Carlo Simulation of the ISX Pumped Limiter*

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Two pumped limters are now operational on ISX, one on the top and one on the bottom of the vacuum chamber.[1] This paper presents the results of Monte-Carlo simulations of the neutral particle transport inside these limiters using the computer code DEGAS.[2] In particular, pumping rates and pressures inside the limiter chamber are calculated and compared with the initial experimental data. The effects of changes in the plasma temperature and density at the limiter slot are also investigated.

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[1]P. Mioduszewski, "Experimental Studies on Pump Limiters," J. Nucl. Mat. 111 and 112, 253 (1982).
[2]D. Heifetz et al., "A Monte-Carlo Model of Neutral-Particle Transport in Diverted Plasmas," J. Comp. Phys. 46, 309 (1982).

Neutral-Particle Transport in the PDX Scoop Limiter and the ALT-I Limiter*

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The transport of neutral deuterium in two pump limiters has been investigated with the 2D Monte Carlo neutral transport code DEGAS [1]. The code incorporates the full set of relevant collision processes (atomic and molecular), and it has a standard wall model which includes fast-neutral reflection and molecular desorption. Quantities predicted by the code which are directly relevant to experiment include the neutral pressure distribution, the pumping rates, and the $H_{\alpha}$ radiation loss. The PDX scoop limiter [2] has been modeled with this code, and the results are shown to be in reasonable agreement with experiment. Motivated by this agreement, we have performed similar calculations for the TEXTOR limiter ALT-I [3], for which data is not yet available. This limiter has a long, narrow duct leading from the scrapeoff region to the pumping chamber, which gives rise to substantially higher ionization probabilities and lower escape probabilities than were found for the scoop limiter. The pressure drop along the duct, the pressure in the plenum, and other pertinent results will be presented for a variety of plasma parameters in the scrapeoff zone.

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[1] D. Heifetz et al., J. Comp. Phys. 46, 309 (1982).
[2] R. Fonck et al., J. Nuc. Mats. 111 and 112, 343-354 (1982).
[3] R. W. Conn et al., Symp. Fus. Tech., Julich, W. Germany (September 1982).

# STABILIZATION OF AXISYMMETRIC MIRRORS BY AN ENERGETIC ION BEAM*

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We examine the stability of axisymmetric mirrors with an energetic ion component to finite azimuthal mode number interchange and ballooning modes. By considering a special class of beam ion orbits (axis encircling) and utilizing the long-thin approximation, we are able to derive a sufficient condition for stability. This condition involves the numerical evaluation of a self-adjoint integro-differential Euler-Lagrange equation on each flux surface $\psi$. Positivity of the quadratic form on each $\psi$ for all azimuthal mode numbers is sufficient for stability to either ballooning or interchange modes depending upon the boundary conditions at the end of each field line. By properly tayloring the beam ion distribution function, we can introduce a stabilizing influence in specified regions along each field line. For example by choosing both $\partial f_b(\varepsilon,\psi)/\partial\psi < 0$ and $\partial f_b(\varepsilon,\psi)/\partial\varepsilon < 0$ in the bad curvature regions, there is a positive-definite contribution to the stability of both ballooning and interchange modes. Whether or not absolute stability is achieved depends upon parameters such as beam density and background density. We will present preliminary numerical results.

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# NEOCLASSICAL TRANSPORT IN A MULTIPLE HELICITY TORSATRON IN THE LOW COLLISIONALITY REGIME*

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In a recent paper,[1] we have shown that a torsatron with multiple poloidal harmonics but only a single toroidal harmonic can be described by a simple model

$$\frac{B}{B_o} = 1 + \varepsilon_T + \varepsilon_H \cos(\eta + \chi) \quad , \tag{1}$$

where $\varepsilon_T(r,\theta)$ and $\varepsilon_H(r,\theta)$ are the effective toroidal and helical modulations, $\chi(r,\theta)$ is a phase angle, and $\eta = \ell\theta - m\phi$. We calculate the neoclassical transport coefficients based on this model in the low collisionality regime ($\nu_{eff} < \omega_b$, the bounce frequency of helically trapped particles). In the strong electric field case ($\omega_E >> \omega_D$, the magnetic drift frequency), besides the usual collisionless detrapping and boundary layer processes, a new effect arises due to the strong pitch angle dependence of the radial drift induced by $\partial\varepsilon_H/\partial\theta \neq 0$. Thus even deeply trapped particles can participate in the transport process. In the weak electric field case ($\omega_E < \omega_D$), the usual plateau and superbanana transport calculations are carried out for the model field Eq. (1). The optimization of the fluxes is performed in terms of the harmonics of $\varepsilon_T$ and $\varepsilon_H$.

*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]K. C. Shaing and S. A. Hokin, ORNL/TM-8556, February 1982.

UCRL ABSTRACT
88694

LINEAR AND NONLINEAR STUDIES OF
RESISTIVE INTERCHANGE MODES IN A REVERSED
FIELD PINCH*

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Studies of resistive interchange modes in a cylindrical reversed field pinch with ZT40-like parameters are carried out both linearly and nonlinearly using the initial value codes ODRIC and TEMCO, respectively. Each code time-integrates the compressible, finite beta, primitive MHD equations written in cylindrical coordinates. The code models include the effects of isotropic viscosity, isotropic thermal conductivity and the Hall current. The nonlinear code TEMCO is fully three-dimensional.

An equilibrium of Robinson[1] known to be stable to tearing modes is used. The Suydam parameter [2] varies with radius so as to allow a realistic central beta.

Parameter space is surveyed linearly to determine the wave numbers of the fastest growing modes. These modes are then followed into the nonlinear regime, where both saturation and mode coupling may be observed.

[1] D. C. Robinson, Nucl. Fus. 18 (1978), 939.

[2] B. R. Suydam, in Peaceful Uses of Atomic Energy 31 (1958), 160.

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# Intensity Correlations of Plasma Radiation*

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An expression for the two-time autocorrelation function of the output of a detector sensitive to the electromagnetic emission of a fully ionized plasma is obtained. Results are given for electron-ion bremsstrahlung and cyclotron radiation. The power spectral density of the intensity fluctuations is calculated for the bremsstrahlung case, and the implications for experimental measurement of plasma properties is discussed.

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# Gyrokinetic Algorithm for Perturbed Distribution Using the Characteristic Orbit

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In many problems of subtle plasma instabilities developments in particle phase space are significant only for resonant particles and those for adiabatic particles may be more readily described. We propose a numerical algorithm to pinpoint the resonant contribution within the particle-code framework. This would allow to study some sensitive structures such as clumps, for example, by isolating the more interesting part of distribution.

For the non-magnetized plasma the solution of the perturbed Vlasov equation

$$\partial_t \delta f + \underset{\sim}{v} \cdot \underset{\sim}{\nabla}\, \delta f + q\underset{\sim}{E}/m \cdot \underset{\sim}{\nabla}_v\, \delta f = -q\underset{\sim}{E}/m \cdot \underset{\sim}{\nabla}_v \langle f \rangle ,$$

with $\partial_t \langle f \rangle = 0$ (Maxwellian), is represented by

$$\delta f = \sum_i w_i[x_i(t), v_i(t), t]\,\delta[x - x_i(t)]\,\delta[v - v_i(t)] ,$$

where $\dot{w}_i = -q\underset{\sim}{E}/m \cdot \underset{\sim}{\nabla}_v \langle f \rangle$, $\dot{\underset{\sim}{x}}_i = \underset{\sim}{v}_i$, $\dot{\underset{\sim}{v}}_i = q\underset{\sim}{E}/m$. This solution can be provided by a particle code with an individual particle carrying its position $\underset{\sim}{x}_i$, velocity $\underset{\sim}{v}_i$, and weight $w_i$, where $\underset{\sim}{x}_i$ and $\underset{\sim}{v}_i$ satisfy the characteristics. For the magnetized plasma the solution of the resonant part of the (simplest) type of gyro-kinetic equation

$$\partial_t g^{(0)} + v_\parallel \hat{b} \cdot \nabla_R g^{(0)} + c\langle \underset{\sim}{E} \rangle_\phi \times \hat{b}/B \cdot \underset{\sim}{\nabla}_R g^{(0)} = q\langle f \rangle / T_i\, \partial_t \langle \Phi \rangle_\phi - c\langle \underset{\sim}{E} \rangle_\phi \times \hat{b}/B \cdot \underset{\sim}{\nabla}_R \langle f \rangle$$

is similarly constructed as $g^{(0)} = \sum_i w_i\, \delta(x - x_i)\delta(v - v_i)$ with $(\underset{\sim}{x}_i, \underset{\sim}{v}_i)$ being guiding center coordinates ($\dot{\underset{\sim}{x}}_i = \underset{\sim}{v}_i$ and $\underset{\sim}{v}_i = v_\parallel \hat{b}$, $\dot{v}_{\parallel i} = qE_\parallel/m$) and

$$\dot{w}_i = q\langle f \rangle / T_i \partial_t \langle \Phi \rangle - c\langle \underset{\sim}{E} \rangle_\phi \times \hat{b}/B \cdot \underset{\sim}{\nabla}_R \langle f \rangle ,$$

where the total distribution $f = \langle f \rangle - q\Phi\langle f \rangle / T_i + g$ and $\Phi$ = the potential. The equation for weight $w_i$ may be advanced in time using the predictor-corrector algorithm.

This work supported by DOE and NSF.

# STABILIZATION OF EXTERNAL IDEAL MHD KINKS BY MEANS OF A LIMITER

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One interesting experimental result from tokamaks is the fact that external ideal MHD kinks are not observed experimentally. These low n number, current driven modes, characterized by a nonzero plasma surface perturbation and a conducting wall at infinity, should be easily detectable experimentally in a variety of low $\beta$ and high $\beta$ situations. One possible explanation for the non-existence of such modes is the presence of a thin metallic vacuum chamber near the plasma. This wall could act like a perfect conductor, producing wall stabilization, on a very fast time scale, but one could argue that on the resistive diffusion time ($\sim$1 msec) it would have no effect. Another explanation, the one considered here, relies on the presence of a limiter. The idea is as follows. Unstable kink modes have a helical mode structure so that in any given poloidal cross section the plasma surface is distorted from its equilibrium shape. Such a perturbation cannot occur if a poloidal limiter is present, as the limiter forces the plasma to maintain its equilibrium shape. This is equivalent to forcing the mode structure to assume the form of a standing wave with a node occurring at the limiter. The standing wave limiter constraint can be thought of as coupling plus and minus n numbers for each m. For kink modes if +n is destabilizing, then -n is stabilizing and the net effect is one of stabilization. Specific results will be presented at the meeting demonstrating this effect. Included in the presentation will be a discussion of the mechanical and magnetic constraints imposed by limiters, a variational formulation of the stability problem, a rigorous solution of a model problem determining the magnetic effects of a limiter and numerical results for a low $\beta$ cylindrical tokamak. We note that limiter stabilization of ideal MHD external kink modes could be important in the following three applications:

1. Providing an explanation for the nonexistence of m=3 external kinks in low $\beta$ ohmically heated tokamaks where $q(a)<3$.
2. Allowing much higher $\beta$ limits in toroidal tokamaks, based solely on ballooning limits. The profiles which maximize $\beta$ for ballooning usually have very low external kink $\beta$ limits, which would no longer be an issue with limiter stabilization.
3. Offering the possibility of removing the conducting wall in a Reversed Field Pinch and replacing it with several poloidal limiters. External kink stability might thus be achieved in a manner much more attractive technologically.

Numerical Studies of Electric Field and Radio-Frequency Wave Driven Run-away Electrons.

E. MOGHADDAM-TAAHERI, K. PAPADOPOULOS, H.L. ROWLAND and L. VLAHOS, Univ. of Md.--A 2-D spatially homogeneous quasilinear code has been constructed using a finite element approach[1]. The code follows $f(v_{\parallel}, T_{\perp}, t)$ and $W(k_{\parallel}, k_{\perp}, t)$. It can be driven by an electric field and/or lower hybrid waves including coulomb collisions or particle losses as an energy sink. Preliminary results from the evolution of the electric field driven run-away tail and the sustained steady-state current driven by radio waves[2], will be presented.

1. Muschietti, K. et al., 1981, Phys. of Fluids, 24, 151.
2. Liu, C.S., et al., 1982, Phys. Rev. Lett., 48, 1479.

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

Signature of APS Member

H.L. ROWLAND
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# A Nonlinear Theory for the Ohm-Navier-Stokes System of Dissipative MHD

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The generalized Ohm's law $\dot{E} = \eta j - v \times B$ is studied coupled with Navier-Stokes-type equations of motion. The asymptotic behavior in time of the solution is studied within the framework of a deterministic theory of turbulence. We introduce a quasi-steady state method to approximate the asymptotic form of the solution decaying to the trivial solution.

We apply the nonlinear semigroup theory [1]. The existence of unique, local-in-time, strong solutions is shown stressing the mathematical analogy of the system with the usual Navier-Stokes equations [2]. For small initial data we prove the existence of global solutions, but, for general initial values, we need higher-order dissipative terms to guarantee the existence of global solutions.

We discuss implications of our work to the quasi-steady state of current-carrying plasmas (tokamaks and reversed-field pinches).

[1] Y. Komura, "Nonlinear Semi-groups in Hilbert Space," J. Math. Soc. Japan 19 (1967) 494.

[2] Z. Yoshida and Y. Giga, "A Nonlinear Semigroup Approach to the Navier-Stokes System," in preparation.

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76ER03077.

# Studies of Ohmic Heating in the Spheromak*

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Time-dependent computational simulations using both single-fluid 0-D and two-fluid 1 1/2-D models are developed for and utilized in an investigation of the ohmic heating of a spheromak plasma. The plasma density and composition, the applied magnetic field, the plasma size, and the plasma current density profile are considered for their effects on the spheromak heating rate and maximum achievable temperature. The feasibility of ohmic ignition of a reactor-size spheromak plasma is also examined.

The ratio between the externally applied magnetic field strength, $B_e$, and the plasma particle density -- plasma radius product, $nr_p$, is proposed as a key parameter in the determination of spheromak plasma heating rates and temperature limits. A recently developed theoretical model(1) predicts large magnetic fluctuations and excessive energy losses for large values of $B_e/nr_p$. A low $B_e/nr_p$, on the other hand, results in excessive radiation losses. In general, the optimum parameter regime for spheromak heating is centered at $B_e/nr_p \sim 1\text{-}5 \times 10^{-20}$ Weber.

The radiation losses and temperature limits in the high-density (low $B_e/nr_p$) regime are found to be especially sensitive to the plasma composition. In particular, concentrations of ~ 1% oxygen and ~0.1% iron place significant limitations on the maximum achievable plasma temperature and cause an enhancement of poloidal flux surface decay. Ideal soft-$\beta$ limits and resistive interchange instabilities are found to provide additional limitations on the heating in small, low-field spheromaks.

The relationship between the initial current profile shape and temperature profile evolution has been considered. Although a flat initial current density profile is desirable, excessive "flatness" leads to the evolution of a hollow temperature profile, hence an enhanced transfer of energy to the edge region of the plasma, causing increased energy losses.

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1. R. E. Olson, PhD Thesis, Fusion Studies Laboratory, University of Illinois, Urbana-Champaign (1983).

* Work supported by US DOE DEAC02 76ET52040.

# PRACTICAL ASPECTS OF AMPLITUDE TRANSPORT IN RAY TRACING CALCULATIONS

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Yale University

## ABSTRACT

The application of geometric optics to high frequency plasma wave heating problems provides a computationally tractable model of wave energy transport and deposition; nevertheless, reliable information can only come from a rigorous construction of the geometric optics field amplitude as well as ray trajectories. Special analyses and computational procedures have been devised to negotiate exceptional circumstances which lead to catastrophe in the amplitude equations due to local failure of the standard geometric optics theory: caustic surfaces and coalescence of local plasma modes. These special treatments are developed in the context of nonhermitian geometric optics for arbitrary background plasma and fields to provide a complete, robust computational prescription for the construction of a plasma geometric optics field excited by an external source.

# STABILITY OF A POLOIDAL CONTROL SYSTEM FOR LARGE TOKAMAKS*

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ABSTRACT

The function of the poloidal control system of a tokamak is to maintain the proper location and cross-sectional shape of the plasma column during the discharge. The control system consists of sensors which detect deviations from the desired location and shape of the plasma and responding amplifiers which adjust currents in the F-coils surrounding the plasma in such a manner that the sensed deviations are counteracted. Our paper describes a method for stability analysis of such a system. The main assumptions are that a linear perturbation treatment of an assumed known equilibrium is valid and that the plasma and the surrounding current carrying elements, namely the F-coils and a resistive vacuum chamber, may be considered axisymmetric.

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

# CURRENT AND PARTICLE DENSITY EFFECTS ON IGNITION IN THE PRESENCE OF SAWTEETH

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The approach to thermonuclear ignition in a toroidal DT plasma has been studied using a one dimensional transport code that includes the effects of high temperature sawtooth oscillations [1]. The periodic disruptions substantially lower the overall rate of plasma heating. The initial work [1] for the specific case of Ignitor has shown that it is possible to attain conditions under which the fusion heating, through the collisional slowing down of the fusion alpha particles, provides more than 20% of the external (in this case Ohmic) heating. The values attained depend strongly on the model adopted for the sawtooth oscillations as well as on the plasma parameters. In particular, only a certain range of plasma current and particle densities correspond to the optimal fusion heating needed to approach ignition (4.5MA and 6.9 - 8.6 x $10^{14}$ $cm^{-3}$, line averaged, for Ignitor). Bremsstrahlung radiation $\sim n^2 T^{1/2}$ determines an inverse relationship between temperature and particle density for temperatures below the value at which fusion heating begins to dominate. Combined with the $T^{-3/2}$ dependence of the Ohmic heating, this determines a maximum density favorable for ignition [2]. These results have important implications for other igniting plasmas.

1. L. Sugiyama and R. Englade, M.I.T./R.L.E. Report PTP 82/14 (1982), submitted to Nuclear Fusion.

2. B. Coppi, M.I.T./R.L.E. Report PTP 82/5 (1982).

STOCHASTIC PARTICLE ACCELERATION INDUCED BY

LOW AMPLITUDE WAVE IN AN INHOMOGENEOUS MAGNETIC FIELD

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The motion of a charged particle in a homogeneous magnetic field under the influence of an externally imposed coherent wave propagating perpendicularly to the magnetic lines has been studied in detail by Karney. We modified Karney's method to include the effect of an adiabatic change in the magnetic field strength as the particle streams along the magnetic field lines. This situation can arise, for example, in tokamak heating experiments. Qualitatively new behavior was observed with the particles diffusing in velocity space for wave amplitude much lower than the stochasticity threshold in the homogeneous magnetic field case. The underlying mechanism of this diffusion is explained and diffusion coefficients are derived both numerically and analytically.

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

# EBT STABILITY FOR ARBITRARY m-NUMBER AND RADIAL PROFILE*

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We consider the macroscopic stability properties of the EBT configuration. Our calculation includes the effects of hot electron FLR, and of both axial and radial dependence of the equilibrium profiles. Further, the ability to treat low m-number modes is retained, as these modes, being global in nature, can more fully sample the complex radial depedence inherent in EBT.

We present here a Vlasov-fluid hybrid calculation (fluid core plasma, Vlasov hot electrons) possessing the features discussed above. An MHD-like energy principle is derived which lends itself to analysis by the existing techniques of theoretical and computational MHD. A variational analysis indicates that hot electron FLR effects operate in the standard fashion to stabilize $m \geq 2$ modes. Interestingly, $m=1$ modes can also be hot electron FLR stabilized, although here the mechanism is somewhat different, relying explicitly on the global nature of the $m=1$ modes to sample the full radial profile of the hot electron ring.

Overall, it is found that, for sufficiently high hot electron beta, finite core plasma betas can be maintained in a manner stable to all MHD-like modes.

*Work supported by the U.S. Department of Energy under Contract No. DE-AC02-78ET-51013.

# PROPAGATION AND ABSORPTION OF ELECTROMAGNETIC WAVES IN FULLY RELATIVISTIC PLASMAS*

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Analytic and numerical calculations have been performed on electromagnetic wave properties in fully relativistic plasmas. The plasma distribution function is assumed to be an isotropic Maxwellian. An arbitrary number of cyclotron harmonics can be retained and all Bessel functions containing finite Larmor radius effects are included without expansion. The complete conductivity tensor $\underset{\approx}{\sigma}$ is computed (including both $\underset{\approx}{\sigma}^A$ and $\underset{\approx}{\sigma}^H$) enabling us to determine the relativistic modification to Re{k} and the electric field eigenvector as well as Im{k}. We find that the locations of the extraordinary mode cutoff and the upper-hybrid resonance are relativistically shifted. At sufficiently high temperature the resonance/cutoff singularity disappears altogether. A result of crucial importance to the heating of the hot electron rings in EBT is that for fixed frequency $\Omega_e/\omega$ the absorption peaks as a function of temperature at some finite $T_e$. For most cases of interest to EBT this peak occurs near $T_e \sim 80$ keV.

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

# QUASILINEAR EVOLUTION OF THE SELF-FILAMENTATION MODE*

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A high-β plasma immersed in a uniform magnetic field with a cross-field electron temperature inhomogeneity may spontaneously develop current filaments aligned with the field. This "self-filamentation" mode, driven by the temperature gradient, is essentially the shear-free version of the temperature gradient driven tearing mode. The concomitant transverse magnetic fields arising from this purely electromagnetic instability bring into thermal contact unequal temperature surfaces thus leading to a quasilinear relaxation of the temperature gradient. An analytical and numerical study of this mode is carried out. Preliminary results showing mode saturation, quasilinear flattening, and anomalous heat transport are presented.

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

# STELLARATOR TRANSPORT MODELING*

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A number of issues related to transport modeling in existing and planned stellarator experiments is addressed. Of particular importance is the transition from an intermediate collisionality regime where transport coefficients scale as $\upsilon^{-1}$ to the low collisionality regime where the scaling changes to $\upsilon$. This transition is shown to occur at relatively high collision frequencies ($\upsilon_{*i} = \nu_i/\varepsilon\omega_b \simeq 10$) and should thus be observable in some existing and planned experiments. Once the transition to the low collisionality regime occurs, electron losses are shown to be a dominant factor in determining the radial electric field, $E_r = -\phi'$, and net confinement properties. Algebraic equations for $\phi'$ yield multiple roots. Analysis of these roots shows that a single root cannot generally be guaranteed to exist at all plasma radii even with a modest range of plasma parameters. Thus the algebraic model leads to discontinuous jumps in the radial field. A differential equation must then be developed for $\phi'$ to provide continuous solutions and thereby smoothly connect the electron-loss dominated regime to the ion-loss dominated regime.

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

# Nonlinear Evolution of Divertor Discharges*

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Recently a new operational regime has been observed in divertor discharges of several neutral beam heated tokamak experiments, including ASDEX, PDX, and Doublet III. This so called H-regime[1] is characterized by good confinement times close to those of ohmic plasmas. We study the characteristics of these discharges using a 3-D MHD code, HIB. The nonlinear development of the plasma is numerically followed from an initial state corresponding to the experiment. Strong resistive instabilities with a dominant m=2 component were observed in the simulation of some PDX discharges. This mode makes poloidal cross sections of the plasma quite elliptic during the nonlinear phase. The edge region including the separatrix quickly becomes stochastic while the magnetic surfaces of the inner region remain intact. This phenomenon may explain the "edge relaxation" which is a characteristic phenomenon of H-mode discharges of PDX. We are currently trying to identify mechanisms which trigger a transition to the H-regime. For these studies the effect of large parallel thermal conductivity $K_{\parallel}$ is important, and this effect is incorporated in the simulation by averaging the temperature along the mangetic field lines.

*Work supported by U.S. DoE Contract No. DE-AC02-76-CHO-3073.
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[1] F. Wagner, et al., Phys. Rev. Lett. 49, 1408 (1982).

# Rotational and Kinetic Effects on Ballooning Modes in Tandem Mirrors*

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A general procedure for examining the influence of rotational, as well as kinetic effects, on the stability of magnetohydrodynamic ballooning modes is presented. The $\underset{\sim}{E} \times \underset{\sim}{B}$ drift due to an unperturbed electrostatic field is included in a gyrokinetic treatment in order to retain rotational effects in the derivation. The ballooning-interchange equation is derived for a long-thin ordering by employing an eikonal ansatz. The derivation permits arbitrary asymmetry and plasma beta and is valid for the fanned fields of tandem geometries. The rotational terms are obtained in the high mode number eikonal limit because $e\Phi/T_i$ is ordered large.

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*Work supported by the U.S. Department of Energy under Contract No. DE-AC03-76-ET-53057 with Science Applications, Inc.

# A CROSS-FIELD STREAMING INSTABILITY WITH ELECTRON TEMPERATURE ANISOTROPY IN TANDEM MIRRORS*

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The kinetic cross-field streaming instability, which is the high beta generalization of the modified-two-stream instability, has been studied in detail, including the effect of an electron temperature anisotropy $T_{\perp e} > T_{\parallel e}$. The mode propagates at oblique angles, much less than 90°, to the magnetic field, and it is not stabilized by electromagnetic effects when the drift velocity exceeds the Alfvén velocity. In fact, it has been shown that this mode is an obliquely propagating whistler wave. The fact that obliquely propagating whistler waves can be amplified by cross-field ion streaming implies that the electron Landau damping is unable to stabilize the growth due to the ion drift. Because mirror machines are often heated by energetic neutral beams injected perpendicular to the magnetic field, it is natural to investigate what happens when both the ion drift and the electron temperature anisotropy are included in the analysis. Since the electrons can be preferentially heated in the transverse direction in a mirror machine, the inclusion of the effect of the temperature anisotropy is not only realistic but also necessary. The present study has found that the temperature anisotropy significantly enhances the peak growth rate. The results have been applied to the end cells of the Tandem Mirror device.

*Supported by ONR and NASA

# SPUTTERING RATES OF DIVERTOR NEUTRALIZER PLATE AND LIMITER SURFACES

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By using a self consistent plasma transport and chemistry code, including non neutral treatment of Debye sheath regions, rates of sputtering erosion of divertor neutralizer plate and limiter surfaces have been calculated. It is found that a local maximum of the self consistent electrostatic potential, $\phi$, occurs away from the material surface. The major cause of sputtering is found to be $H_2^+$ ions which are produced from $H_2^o$ emitted from the surface, are electron impact ionized before reaching the peak of $\phi$, and are returned to the surface by the electrostatic field. Comparisons with fluid model estimates of sputtering in the higher range scrape off plasma temperature where a kinetic model is to be applicable, show higher sputtering rates from the kinetic model. Reduced scrape off temperatures at which sputtering rates would be acceptable are calculated.

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1. Plasma Fusion Center, MIT.

2. Phys. Rev. Lett. 49, 650(1982).

# TRANSPORT THEORY FOR TURBULENT PLASMAS: MICROSCOPIC REVERSIBILITY, THE ONSAGER RELATIONS, AND BROKEN SYMMETRY*

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A general formulation of transport theory is given which is capable of treating, in a common framework, collisions and turbulence in a complex magnetic geometry. The type of turbulence considered is restricted but only by some properties generic to practical fusion confinement schemes that permit a transport equation description. The theory is based on an underlying Fokker-Planck kinetic equation which is applicable for very general scattering processes and collisionality ranges.[1] One can establish basic symmetries of the transport matrix that are a consequence only of microscopic reversibility in the underlying dynamics. These Onsager relations are fundamental and persist for turbulent scattering. However, in contrast to what is generally assumed, these symmetry relations do not apply to the entire transport matrix but only to those fluxes associated with scattering processes. There is another class of fluxes, essentially kinematic in nature, that do not, in general, obey Onsager relations. The conjugate coefficients result from independent kinematic flows, not inverse scatterings and cannot, therefore, be linked by microscopic reversibility.

In summary, the full phenomenological matrix relating the fluxes to the forces is not symmetric, in general. It can be made symmetric by removing certain kinematic flows which can be identified. If the remaining coefficients are regarded as the transport matrix, then the Onsager reciprocal relations apply.

Specific examples in the tokamak will be discussed.[2]

*Work supported by the U.S. Department of Energy under Contract No. DE-AC02-78ET-51013.

[1]Generalizing a previous transport theory, I.B. BERNSTEIN and K. MOLVIG, Phys. Fluids (to be published).

[2]K. MOLVIG, L.M. LIDSKY, K. HIZANIDIS and I.B. BERNSTEIN, COMMENTS ON MODERN PHYSICS: PART E, 7, 113 (1982); also J.W. JOHNSON, K. HIZANIDIS, L.M. LIDSKY and K. MOLVIG (SHERWOOD MEETING, 1983).

# FINITE ORBIT ANALYSIS FOR LONG WAVELENGTH MODES IN A PLASMA WITH A HOT COMPONENT*

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Recent eikonal calculations[1,2] of the stability of plasmas with a hot component, such as the hot electrons in EBT, indicate a strong, hot component finite gyroradius effect that stabilizes curvature driven modes at all $\beta$ if $k_\perp^2 \rho_h^2 R/\Delta_B \gtrsim 1$ ($k_\perp$ = radial wave number, $\rho_h$ = hot component gyroradius, $R$ = radius of curvature, $\Delta_B$ = magnetic scale length). In the present work we investigate the finite orbit effects on long wavelength modes which have recently been shown to be the most pessimistic of the curvature driven instabilities.[3] The equations are derived from an exact Vlasov variational principle for the z-pinch model. One result of the analysis is that the finite gyroradius terms vanish if the perturbed magnetic field, $\delta B$, is proportional to the radial gradient of the unperturbed field, $\partial B/\partial r$, as occurs for the usual MHD ordering. For the low frequency ordering of the hot component theory, however, $\delta B \not\propto \partial B/\partial r$ when the Lee-Van Dam parameter, $\tilde{\beta} \equiv \beta_c(R/\Delta)$, ($\Delta$ = pressure gradient scale length, $\beta_c$ = core plasma $\beta$) is of order unity. A strong finite orbit effect, of order $\varepsilon \equiv \tilde{\beta}\, \rho_h^2/\Delta^2\, R/\Delta_B$, is then a possibility. While the finite orbit terms in the equations can be large, their effect on stability limits is not found to be substantial. The large $\varepsilon$ limit is analytically tractable, yielding a small (approximately 30%) shift of the zero orbit Lee-Van Dam limit. A new, weakly destabilizing, dissipative drive is found to arise from singular structure of the finite gyroradius operator.

[1] H.L. Berk, C.Z. Cheng, M.N. Rosenbluth, J.W. Van Dam, IFS Report 69, Institute for Fusion Studies, Austin, TX, 1982.
[2] H.L. Berk, J.W. Van Dam, D. Spong, to be published in Phys. Fluids.
[3] K.T. Tsang, P. Catto, SAI Report PRI-34, Sci. Applications, Boulder, CO, 1981.

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BAL - A Balloon Code for the 80's

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Ideal and resistive MHD ballooning modes are believed to be involved in both the gross stability limits and the microinstabilities and anomalous transport governing high-$\beta$ tokamaks and other toroidal confinement systems. The introduction of the ballooning representation in 1977 was a major step toward effective computation of these modes in sheared toroidal fields. Nevertheless, the balloon codes that have been developed so far suffer from a number of numerical difficulties which make them cumbersome, time-consuming, and inaccurate. A new code has been developed to remedy these problems. To avoid the fixed grid and the idiosyncrasies of particular equilibrium solvers, the equilibrium fields are represented by Fourier series which can be computed by an interface subroutine for any equilibrium. Integration is then performed very efficiently by an adaptive method which is free to choose its own step size because it is not tied to a fixed grid. A major problem for all balloon codes is the slowness of convergence at large values of $\theta$ for small values of resistivity and growth rate. The new code achieves substantially accelerated convergence be fitting the numerically computed solution to an asymptotic series at large $\theta$, computed to arbitrarily high order and truncated at an optimal number of terms. The resulting code is fast, accurate, and automatic. It presently treats ideal marginal, ideal nonmarginal, and resistive ballooning modes with full compressibility in any axisymmetric equilibrium. Short-range plans center on the inclusion of viscosity and other nonideal effects. Longer-range plans include treatment of nonaxisymmetric systems, radial mode structure, and nonlinear aspects.

# RELATIVISTIC 2-DIMENSIONAL THEORY OF LOWER-HYBRID CURRENT DRIVE*

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The quasilinear theory of Fisch [1] is extended to include relativistic effects, as well as dependence of the tail perpendicular temperature $T_\perp$ on the parallel momentum, $p_\parallel$. The relativistic generalization is motivated by the fact that the RF spectra have phase velocities that extend into regions where relativistic effects must be taken into account (e.g. phase velocity corresponding energies in Alcator C: $\approx 30-170$ keV, in PLT: $\approx 30-500$ keV). As far as the $p_\parallel$-dependence of $T_\perp$ is concerned, recent experiments on PLT and Alcator C seem to indicate perpendicular temperatures of the current carrying electrons in the tail considerably higher than the temperature of the thermal bulk, $T_B$ [2-3]. The problem we solve [4] is a two-dimensional Fokker-Planck equation describing the quasilinear relaxation due to the RF spectrum in the presence of collisions and with relativistic effects taken into account. The RF spectrum applies in the region $p_0 \leq p \leq p_1$ where $p_0$ and $p_1$ are the left and right matching momenta which respectively connect the region under consideration to the thermal bulk and an outer tail. The distribution is modeled by $f(p_\parallel, p_\perp) = \exp[-p_\perp^2/2m_eT_\perp(p_\parallel)]F(p_\parallel)/2\pi m_e T_\perp(p_\parallel)$. Integrating the Fokker-Planck equation for $f(p_\parallel, p_\perp)$ over the perpendicular momenta, one obtains an equation for $F(p_\parallel)$ whose quasisteady solutions in the regions I: $(p \leq p_0)$, II: $(p_0 \leq p \leq p_1)$, III: $(p_1 \leq p)$ (suppressing the subscript "$\parallel$") are,

$$F(p) = F_j \exp\left(-\int_{p_j}^{p} p\frac{\gamma\left[2\varsigma\left(1+\frac{1}{p}\frac{dT_\perp}{dp}\right)+\gamma\right]}{2D_jp^2+2\gamma T_\perp\varsigma+\gamma^3}dp\right) \quad ; \quad j = I, II, III \tag{1}$$

where $p_{II} = p_0$, $p_{III} = p_1$, $D_I = D_{III} = 0$ and $D_{II} = D_0$; also $\varsigma = (Z+1)/2$ with $Z$ being the ion charge number and $\gamma^2 = 1 + p^2\beta_{TH}^2$ with $\beta_{TH} = v_{TH}/c$. The quantities $p$, $T_\perp$, $D_0$ are normalized as follows: $p \to p/\sqrt{m_eT_e}$, $T_\perp \to T_\perp/T_e$, $D_0 = D_{QL}p/m_eT_B\nu$, where $\nu = 8\pi e^4 n_e\Lambda_{ee}/m_e^{1/2}T_B^{3/2}$ is the collision frequency and $D_{QL}$ the quasilinear diffusion coefficient. In obtaining Eq. (1) it has been assumed that the parallel flux is zero everywhere. The perpendicular temperature profile, $T_\perp(p_\parallel)$, is evaluated by taking the energy moment $(2\pi\int dp_\perp p_\perp^3)$ of the Fokker-Planck equation and setting $\frac{\partial T_\perp}{\partial t} = 0$. By using this procedure one obtains two ordinary differential equations for $T_\perp$ in regions II and III (assuming that $T_\perp = 1$ in region I) which introduce four undetermined constants. In region II the assumption $D_0p^2 \gg \max T_\perp(p)$ is also used to the extent that one deals with RF-spectra which are consistent with this assumption. The aforementioned four constants together with $F_I$, $F_{II}$ and $F_{III}$ constitute a set of seven unknowns. These are determined upon matching the values of $F(p)$, $dF(p)/dp$ and $T_\perp$ on the boundaries at $p = p_0$ and $p = p_1$ demanding $\int_{-\infty}^{+\infty} dp_\parallel F(p_\parallel) = 1$. Our model predicts a considerable perpendicular temperature in the RF-generated current carrying electrons. Results on current generation, efficiency, and $T_\perp(p_\parallel)$ as functions of the applied RF spectra will be presented.

*This work is supported in part by NSF Contract No. ESC-79-07-047 and in part by DOE Contract No. DE-AC02-78ET-51013.

## REFERENCES

1. N. J. Fisch, *Phys. Rev. Lett.* 41, 873 (1978).
2. J. J. Schuss, Proc. 24th Annual Meeting APS/Plasma Physics, 3A3 (1982).
3. F. H. Tenney, M. Bitter, K. W. Hill, S. Sesnic, and S. van Goeler, Proc. 24th Annual Meeting APS/Plasma Physics, 6P17 (1982).
4. K. Hizanidis, V. Krapchev, and A. Bers, Fifth Topical Conference on Radio Frequency Plasma Heating, B-1.9, Univ. of Wisconsin, Madison, WI, Feb. 21-23, 1983.

# Diffusion of Transiently Trapped Test Particles

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When the trapping frequency $\omega_t$ becomes large compared to a diffusion time $T_d$, $\omega_t T_d > 1$, one expects that the dynamics of a test particle is not well described by either quasilinear or resonance broadening theories.

Although the DIA may be a more accurate theory in the above regime, the complexity of even the test particle DIA makes an analytic treatment very difficult, and discourages a numerical analysis.

The Schrödinger equation with a time-dependent potential exhibits behavior similar to the test particle Vlasov equation with a corresponding electric field, but the numerical solution of the DIA is far simpler for the former.

For the special case of a Kubo Anderson Process potential, the solutions of the DIA and a resonance broadening theory are compared with the actual mean solutions to the Schrödinger equation. It is found that the actual response function has multiple broadened resonances, some of which correspond to transient localized eigenstates of the Schrödinger equation. There is a regime, $\omega_c T_d$ is "large" but not "too large," where the DIA is qualitatively more accurate.

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ABSTRACT

1983 Controlled Fusion Theory Conference

# Numerical Studies of the Collisional Drift Wave in Toroidal Geometry

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Results from many tokamaks, including the Caltech Research Tokamak[1] and the Alcator A tokamak[2], show that the edge plasma is often very turbulent with large density fluctuations ($\tilde{n}/n \sim 50\%$) and broad frequency spectra in the drift wave range. Measurements of the large particle transport caused by these fluctuations were reported in Ref. 1. Since improvement in the (edge) particle confinement is one of the signatures of the H-type discharges in the Asdex tokamak[3], the edge turbulence may be a relevant factor in determining the global energy confinement of a discharge. One possible cause of this turbulence is the collisional or dissipative drift wave since the collisionality of these edges plasmas is typically of order unity, e.g.

$$\nu_{ei}\, qR\Big/\sqrt{T_e/m_e} \simeq 1.$$

Here we present results from a numerical study of the collisional drift wave in toroidal geometry. The linearized time-dependent equations for the mode are advanced numerically, and the eigenvalues and eigenfunctions are found by analyzing the late-time behavior. This work is the first step in a nonlinear study in which mode coupling effects from the ion nonlinearities will also be included.

In this treatment, the significant features of the collisional drift wave are reproduced: (1) When the (linear) mode coupling effects caused by the toroidal geometry are neglected, and thus the equations reduce to the sheared-slab equations, the mode is shear damped[4]; (2) When the toroidal mode coupling effects are included, the eigenfunction becomes localized and the mode becomes unstable[5]; (3) For low-collisionalities, the growth rate increases as the square of the collision frequency for fixed mode number. Results will be presented for parameters typical of the edge region of the Caltech Research Tokamak.

1. S. Zweben, P. C. Liewer, and R. W. Gould, J. of Nucl. Materials 111 & 112 (1982) p. 39.
2. R. E. Slusher and C. M. Surko, PRL 40 (1978) p. 400.
3. F. Wagner and Asdex Group, PRL 49 (1982) p. 1408.
4. Liu Chen et. al. Nuc. Fus. 19 (1979) p. 373.
5. L. Chen, M. S. Chance, and C. Z. Cheng, Nuc. Fus. 22 (1982) p. 293 and Nuc. Fus. 20 (1980) p. 901; R. Marchand and P. N. Guzdar, Nuc. Fus. 22 (1982) p. 289.

# Arresting the Ballooning Mode

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Three-dimensional tokamak equilibria that are stable to ideal, high-n ballooning modes exist as bifurcations of axisymmetric equilibria at critical beta values. External coils to guide the nonlinear development of the plasma into a stable configuration are recommended.

The lowest order nonlinear contributions to the perturbed energy are determined in Euler coördinates. A finite dimensional projection of the energy functional for the ballooning perturbation, as was demonstrated for the axisymmetric mode (1), permits a description of the bifurcated equilibria and their stability by a transformed potential energy function. Thom's theorem is applied to analyze its morphogenesis.

The helical bulging of the ballooning perturbation requires modification by an active system of external coils to produce saturation. A preliminary design is sketched. Above the first or below the second critical beta an hysteresis cycle of operation between bifurcated equilibria is attributable to plasma heating and transport.

(1) D J Elkin and S Johnston, Sherwood Theory Meeting 1982 (2D17)

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# EFFECT OF MAGNETIC BENDING ON THE EBT HIGH FREQUENCY STABILITY*

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It has been shown recently that both the high frequency cold plasma density gradient drift wave and the compressional Alfvén wave can be driven unstable through interaction with the hot electron magnetic curvature drift wave in the ELMO Bumpy Torus (EBT) device. In this work we remove the flute assumption and thus allow for a finite amount of magnetic field line bending. The dispersion relation must then account for both the shear Alfvén branch together with the modification in the three waves mentioned above. In general, two types of new instabilities are found. They result from the coupling of the hot electron drift wave to both the shear Alfvén and the high frequency drift waves. The stability conditions will be presented.

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# Radial Structure of Drift Cyclotron and DCLC Eigenmodes in Cylindrical Geometry*

by

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## ABSTRACT

Drift cyclotron and DCLC eigenmodes and growth rates are calculated in cylindrical geometry. The calculations allow an arbitrary value of the ratio of gyroradius to density scale length, and they produce an explicit representation of the radial structure of the mode in an inhomogeneous plasma, even for low radial or azimuthal mode numbers. No WKB approximation is made; instead, the exact integral equation describing the plasma response is solved by a combination of analytical and numerical techniques. The model employed is electrostatic, with a uniform background magnetic field. The stability boundary of the DCLC mode in parameter space is calculated.

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# MHD EQUILIBRIA WITH HELICAL SYMMETRY IN THE PRESENCE OF PURELY HELICAL FLOW*

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Flow effects on static helical equilibria in straight geometry have been investigated in terms of the ideal magnetohydrodynamic (MHD) equations. Although the lines of force of the flow lie on the magnetic surfaces in the presence of helical symmetry, the magnetic and constant pressure surfaces are distinct in the presence of flow. If the flow is purely helical, the ideal MHD equations can be reduced to a single partial differential equation for the flux function $\psi$.[1] The equation contains four free functions of $\psi$ which have to be specified together with the boundary conditions on $\psi$.

If the functions are linear in $\psi$, an exact solution in terms of Bessel functions exists for $\psi$. Studies of this solution have proceeded in two ways: (i) analytically via expansions in terms of small distances about the magnetic axis, and (ii) numerically. Stationary equilibria and equilibria with helical flow are compared for a plasma contained in a perfectly conducting cylinder.

The analytic studies suggest the existence of critical flow velocities at which the nature of the magnetic configuration changes. Specifically, new magnetic axes appear which do not exist in static equilibria. The new axes may be the source of island formation which may result in enhanced plasma loses. Preliminary numerical studies also suggest that increased complexity of magnetic island structure may be expected.

*Work supported in part by D.O.E. contract #AS02-78ET53082.

[1]Y.Z. Agim, L.C.S. Goes, and J.A. Tataronis, Bull. Am. Phys. Soc. 27, No. 8, Part II, p. 1019 (1982).

# Tokamak Ripple Transport, Revisited*

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An improved description of collisionless particle orbits and a closer look at the appropriate boundary condition to impose in determining the perturbed distribution function $f_1$ rectifies a number of deficiencies in previous theories[1,2] of low-collisionality tokamak ripple transport.

Previous work assumes that the time $\tau_r$ an entrapping particle spends ripple trapped is large compared with the time $\tau_t$ it spends toroidally trapped. If this assumption is made, the proper expression for the portion of diffusion coefficient D linear in $\nu$ is $D_{1r} \sim \nu r^2/(\alpha^2 \varepsilon^{1/2})$, completely different from the previous result $D_{1t} \sim \nu r^2/(\alpha^5 \delta^{1/2})$. (Here, $\alpha \equiv \varepsilon/Nq\delta$, as usual). In addition, in this case there is also a contribution $D_{1/2} \sim \nu^{1/2}$ to D arising from a discontinuity (at $\nu = 0$) in $f_1$ between those toroidally-trapped particles whose turning points are on either side of the point $\theta_m$ at which $\alpha|\sin \theta_m| = 1$.

If on the other hand the <u>opposite</u> assumption $\tau_t \gg \tau_r$ is made, D is indeed given by $D_{1t}$, but with a numerical coefficient about three times larger than in Ref. 1, owing to the different boundary conditions.

*Work supported by the U.S.DOE under contract number DE-AC02-78 ET53082.

1. K.C. Shaing, J.D. Callen, Nucl. Fusion <u>22</u> (1982) 1061.
2. P.N. Yushmanov, Nucl. Fusion 22 (1982) 315.

# PLATEAU REGIME TRANSPORT FOR PLASMAS WITH STRONG TOROIDAL ROTATION*

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Due to strong parallel neutral beam injection tokamak plasmas with toroidal rotation velocity $v_\phi \lesssim v_{thi}$, $v_\phi > v_{thI}$ (where $v_{thi}$, $v_{thI}$ are the hydrogen/impurity thermal speeds) have been produced. From E + v × B = 0 this implies a new ordering for the large ensuing radial and poloidal ambipolar electric fields, in the neoclassical theory. Using this ordering, the drift kinetic equation (D.K.E.) is solved in the plateau regime. The large toroidal rotation produces off-diagonal elements in the stress tensor $\overleftrightarrow{\pi}$ of the order $(\rho_i/r_n)^2$ without having to expand the D.K.E. through $(\rho_i/r_n)^4$ as is necessary to calculate the perpendicular viscosity $\eta_\perp$ in the standard ($v_\phi << v_{th}$) theory.[1] The plateau regime result is $\eta_\perp = .28\, n_i\, \rho_i^2\, q^2\, \nu_{ii}$, similar in appearance to the banana regime result of Refs. 1,2. Particle and heat flow transport coefficients are also calculated as a function of $(v_\phi/v_{thi})$. For $v_\phi/v_{thi} = 1$ the enhancement of $\chi_i \approx 2$. Besides the friction driven particle flux $\Gamma_1$, due to the large flow velocity $v_\phi$ a perpendicular viscosity driven flux $\Gamma_2$ arises. One finds $\Gamma_2/\Gamma_1 = (v_\phi/v_{thi})(\rho_{pi}/r_n)\cdot\sqrt{(m_i/m_e)}(\nu_{ei}/\omega_{te})$, which, for the "maximal ordering" $\sqrt{m_i/m_e} \lesssim (r_n/\rho_{pi})$ (such that electron-ion equilibriation equals ion heat conduction in the tokamak), can imply $\Gamma_2$ to be important for the particle balance. While $\Gamma_1$ is automatically ambipolar, $\Gamma_2$ is so only after a few perpendicular viscosity times $(r_n^2/\eta_\perp)$. After this transient, $E_r$ is adjusted such that $\sum_a < R^2 \nabla\phi \cdot (\nabla \cdot \vec{\pi}_a - \vec{\kappa}_a) > = 0$ where $\vec{\kappa}_a$ is the momentum input to species a from the beam.

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

[1] Rosenbluth, Rutherford, Taylor, Frieman and Kovrizhnikh, IAEA CN/28/C-12, 1970.
[2] Tsang, Frieman, Phys. Fl. 19, 747 (1976).

# TOROIDAL MOMENTUM CONFINEMENT IN BEAM HEATED TOKAMAKS*

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Several aspects bearing on momentum confinement analysis are treated.

Modified Stix coefficients are derived for momentum and energy transfer from fast ions to a streaming background plasma. The incremental coefficients vary as

$$\text{(Momentum)} \quad \delta K_i \;\alpha\; \left(\frac{e_i}{e_b}\right)^2 \left(\frac{m_i + m_b}{m_b}\right) \frac{v_\phi}{v_c} / \cos\,\theta_o$$

$$\text{(Energy)} \quad \delta G_i \;\alpha\; \left(\frac{e_i}{e_b}\right)^2 \left(\frac{m_i + m_b}{m_b}\right) \frac{v_\phi}{v_c} \cos\,\theta_o$$

i and b refer to plasma and beam, $\theta_o$ is the injection angle, and $v_c$ is the critical velocity denoting transition from electron to ion slowing. The increments arise from modifications to the Rosenbluth potentials by the presence of flow; numerical results are presented both for the conventional assumptions ($v_e >> v_b >> v_i$) and with the unexpanded potentials. Monte Carlo (3D) modeling of 'halo' neutrals, which are produced by charge exchange of the injected neutrals with the background, show a significant enhancement of the halo neutral density when there is a toroidal flow ($v_\phi/c_s \approx 0.3$). Halo neutrals are then preferentially produced in a direction requiring long escape times. Charge exchange losses of momentum are enhanced.

An ad hoc momentum confinement model, using the new Stix coefficients, charge exchange effects, and based on previous fluid-regime diffusion calculations, is proposed to satisfy available data from ISX-B.

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# FOKKER-PLANCK CALCULATIONS FOR HOT ELECTRON STARTUP IN MFTF-B*

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Problems associated with the formation of hot electrons by ECRH in end plugs of MFTF-B are being investigated using a multi-region Fokker-Planck code.[1] One possible scenario is the following: after forming a low density ($n \simeq 5 \times 10^{11}$ cm$^{-3}$), low temperature ($T_e \leq 100$ eV) plasma in the central cell we turn on ECRH in the end plug (or anchor) to form hot electrons of density 2-3 x $10^{12}$. We then inject neutral beams to establish sloshing ions and at about the same time turning on additional ECRH power to heat the potential-trapped warm electrons. In this startup process we are concerned about issues such as buildup time, ECRH power requirements, hot electron energy limits, and the effects of cold electrons produced by neutral beam injection. We study these problems using the Fokker-Planck code, taking into account the ambipolar potential being formed. The results of these calculations will be reported.

[1]Y. Matsuda, J.J. Stewart, Bull. Amer. Phys. Soc. 27, 1116 (1982).

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# A New Approach to Tandem Mirror Coil Design*

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A technique is developed to obtain coil configurations which reproduce given magnetic fields near the magnetic axis for a quadrupole-stabilized mirror (simple or tandem). Using the Biot-Savart Law for the paraxial fields, the problem is reduced to a pair of coupled nonlinear integral equations. These are solved iteratively for a given (filamentary) coil representation. By computing only the paraxial magnetic field, a great savings in computer time and storage is obtained. The desired magnetic induction B(z) and fanning profile f(z), given to the coil code as input, are typically reproduced by the resulting coil configuration to within 1% using a modest amount of computer time. By means of this technique, previous work on optimizing the paraxial field profiles for stability and transport[1-3] can be used as a practical guide to coil design.

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[1] P. J. Catto and R. D. Hazeltine, Phys. Rev. Lett. 46, 1002 (1981) and Phys. Fluids 24, 1663 (1981).

[2] J. R. Myra, D. A. D'Ippolito and P. J. Catto, SAI Report No. SAI-254-82-174-LJ/PRI-44 (1982); Phys. Fluids 26, (1983).

[3] D. A. D'Ippolito, J. R. Myra, P. J. Catto and G. L. Francis, SAI Report No. SAI-254-83-348-LJ/PRI-58 (1983).

*Work supported by U. S. Department of Energy Contract No. DE-AC03-76-ET53057 with Science Applications, Inc.

# Interchange Stability of a Plasma in the Presence of Coherent, High Frequency Oscillations*

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In addition to causing anomalous particle losses, high frequency oscillations in a mirror plasma are of potential importance because they can couple nonlinearly to low frequency (eg. MHD) modes. There are examples in the theoretical literature where such interactions are both stabilizing[1] and destabilizing.[2] These observations have helped to motivate our study, in which we consider the interchange stability of a plasma which also supports a single, coherent, electrostatic wave in the ion cyclotron frequency range. The calculations emphasize the importance of insuring ambipolarity in the nonlinear state. Retaining the effect of the high frequency fluctuations on the background distribution function, as well as nonresonant mode coupling, we are employing the model to obtain an estimate of the high frequency wave amplitude necessary to modify the usual interchange stability criterion.

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*Work supported by the U. S. Department of Energy under Contract DE-AC03-76-ET53037 with Science Applications, Inc.

[1] G. Berge, Nucl. Fusion 12, 99 (1972)

[2] D. R. Nicholson, R. E. Aamodt, and C. S. Liu, Phys. Fluids 22, 114 (1979).

TRANSPORT OF ENERGY, ANGULAR MOMENTUM AND IMPURITIES IN NEUTRAL BEAM HEATED TOKAMAKS*

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ABSTRACT

Neoclassical transport in tokamak plasmas rotating toroidally at speeds comparable to impurity thermal speeds has been considered. The effect of rotation on impurity transport has been investigated, for general magnetic geometry. Also, the role of impurities in energy and angular momentum transport has been investigated. Transport coefficients for the Pfirsch-Schlüter regime will be presented.

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# Magnetic Coordinate Representation of Stochastic Magnetic Fields*

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The presence or absence of magnetic surfaces has an enormous effect on the confinement properties of toroidal devices such as tokamaks and stellarators. It is, therefore, important to have a simple representation of the apparently complex state of stochastic field lines. In magnetic fields with perfect surfaces, magnetic coordinates are known to greatly simplify the study of plasmas in complicated fields. The coordinates $\psi$, $\theta$, $\phi$ represent the field by the well-known form

$$\vec{B} = \vec{\nabla}\psi \times \vec{\nabla}\theta + \vec{\nabla}\phi \times \vec{\nabla}\psi_p(\psi)$$

The angles $\theta$ and $\phi$ are a poloidal and a toroidal angle. The toroidal magnetic flux inside a surface is $2\pi\psi$ and $2\pi\psi_p$ is the poloidal flux outside the surface. This representation can be extended to stochastic fields with the representation

$$\vec{B} = \vec{\nabla}\psi \times \vec{\nabla}\theta + \vec{\nabla}\phi \times \vec{\nabla}\Psi_p(\psi,\theta,\phi).$$

The flux function $\Psi_p(\psi,\theta,\phi)$ has the important interpretation as the Hamiltonian which has the field lines as its trajectories. The evaluation of these generalized magnetic coordinates, given $\vec{B}(\vec{x})$, will be discussed as well as several applications.

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# STATISTICAL PROPERTIES OF DRIFT WAVE TURBULENCE

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The statistical properties of turbulence produced by the dissipative electron drift wave instability are studied further using the mode coupling equations given earlier.[1] The chaotic attractor behavior of the wave coupling process is well known.[2] Using a $15 \times 15$ truncated $\vec{k}$ space, the exact phase dependent equations are integrated in the $N = 224$ dimensional phase space. In addition, the renormalized turbulence theory equations are integrated for the $N^{RPA}=112$ phase averaged spectral intensities $I_{\vec{k}}(t)$.

Earlier work on comparing the spectral features $\omega_{\underset{\sim}{k}}^{n\ell}$, $\nu_{\underset{\sim}{k}}^{n\ell}$ derived from the simulation frequency spectra with the corresponding values predicted by renormalized turbulence theory is continued.

To consider the question of the onset of strong correlations we introduce statistical studies of the time series $\varphi(t)$ and $\varphi_{\underset{\sim}{k}}(t)$. The probability distributions of the fields $\varphi$ and $\varphi_{\underset{\sim}{k}}$ are compared with the gaussian-normal distribution. We compute the skewness and the fourth cumulant for these fields.

1,2. P.W. Terry and W. Horton, Phys. Fluids 26, 106 (1983) and Phys. Fluids 25, 491 (1982).

Work supported by DOE Contract DE-FG05-80ET-53088.

# TRANSPORT INSTABILITIES IN TANDEM MIRRORS AND THE GUNN EFFECT*

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The radial particle flux $\Gamma$ in the center cell of a tandem mirror depends on the radial electric field E. In the resonant transport regime there is a range of values of E for which $\partial\Gamma/\partial E < 0$; this has been shown to lead to singularities in the solution of the charge-balance equation which determines E.[1] An analogous phenomenon ("negative differential mobility") in some solid state devices causes the Gunn effect: generation of travelling waves of density or electric field. The possibility of the occurrence of radially propagating travelling waves in the center cell of a tandem mirror is assessed, using model transport equations.

[1]A.A. Mirin, S.P. Auerbach, R.H. Cohen, J.M. Gilmore, L.D. Pearlstein, M.E. Rensink, LLNL Rept. UCRL-88287 (1982). To be published in Nucl. Fusion.

[2]J.B. Gunn, J. of the Phys. Soc. Japan 21 (Supplement), 505 (1966).

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# RESISTIVE BALLOONING MODE STUDIES*

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A set of linear resistive ballooning equations is derived including the effects of parallel dynamics and F.L.R. terms. Anomalous resistivity and electron viscosity terms derived from a renormalized theory of the turbulent ballooning spectrum, may also be included. These equations are solved as an initial value problem in ballooning space.

The transition from resistive to ideal ballooning will be examined for a sequence of varying Beta equilibria, derived from a reconstructed ISX-B equilibrium. The effects of parallel dynamics will be shown to be in good agreement with analytic results. The stabilizing influence of diamagnetic effects, predicted analytically, will be examined. Nonlinear extensions of this formulation will be discussed.

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# Criterion for Baldwin Instability in a Symmetric Tandem Mirror with Hot Electron End Plugs*

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The stability of a symmetric tandem mirror with hot electron end plugs against low frequency modes ($\omega < \Omega_i$) is investigated using a model first proposed by Baldwin. The Baldwin instability, which is due to the coupling of a flute negative energy mode in the plug and a sinusoidal shear Alfven mode in the center cell, is recovered when the spatial resonance due to the vanishing of the electromagnetic part of the local dispersion function is ignored. When the Lee-Van Dam criterion in the plug is satisfied the system can be unstable due to this coupling, provided that the length of the center cell, $L_c$, falls in certain ranges of values. However, under modest restriction of parameters, these unstable regions impose little limitation on the center cell length.

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# CONCEPTS IN WAVES*

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The geometric optics limit and the transition to wave incoherence is studied via renormalization group techniques. We exhibit several general features of wave evolution based on simple examples. We first describe the hierarchy of scales implicit in a wave system. We begin with the canonical infinite dimensional Hamiltonian structure for waves. We develop the relevant statistical assumptions to allow reduction by phase symmetry. This leads to a Lie-Poisson bracket for the eikonal waves. We explore the effect of chaotic ray trajectories on wave evolution and develop a formalism for energy transport. We study the effect on the waves of Smale horseshoes in the ray trajectories (which occur at any transversal intersection of the stable and unstable manifolds of a closed ray). This study leads us to a series of approximate Hamiltonian descriptions for each length scale, related to one another by a renormalization group transformation. We explicitly exhibit the so-called "diffractals" of M. Berry and show that fractal scaling only obtains in the neighborhood of a hyperbolic fixed point of the renormalization transformation. Explicit connection is made with the scaling in geometric diffraction theory and connections with weak turbulence theory are suggested.

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# MONTE CARLO CALCULATION OF THE NEOCLASSICAL PINCH EFFECT*

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This paper presents a numerical (Monte Carlo) calculation of the neoclassical pinch coefficient designed to test the idea[1] that scattering in the boundary layer between trapped and circulating space can modify the flows in such a way as to break "Onsager" symmetry.[2] The results confirm the ideal banana regime predictions[3] and demonstrate several effects that modify the flow as predicted in Ref.[1]. The ideal banana theory predicts that the trapped particle contribution (the Ware effect) to the transport coefficient will be cancelled by an outward flow of particles near the trapped-circulating boundary. The addition of scattering will "smear out" the boundary layer, leaving the Ware effect intact.

It is found that the non-turbulent results are in good agreement with the theory for low values of the toroidal electric field. At larger values of $E_\phi$, non-linear effects reduce the contribution of the boundary layer particles to the overall transport coefficient.

Turbulence and/or collisions are simulated by Monte Carlo methods. The transport coefficient is calculated for several values of the effective collision frequency $\nu_*$. At low scattering levels, $\nu_* \sim 10^{-4}$, the boundary layer contribution to the transport coefficient is reduced by a factor of 10, while the trapped particles are unaffected.

*Work supported in part by the U.S. Department of Energy under Contract No. DE-AC02-78ET-51013.

[1] K. MOLVIG, L.M. LIDSKY, K. HYZANIDIS and I.B. BERNSTEIN, COMMENTS ON MODERN PHYSICS: PART E, 7, 113 (1982).

[2] K. MOLVIG, K. HIZANIDIS, SHERWOOD MEETING (1983).

[3] I.B. BERNSTEIN and K. MOLVIG, Phys. Fluids (to be published).

# RELATIVISTIC EVOLUTION OF ELECTROMAGNETIC INSTABILITIES*

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The space-time asymptotic pulse shape for linear instabilities is obtained by applying the theory of pinch-point analysis[1] to observers moving with non-relativistic velocities.[2] Such an analysis is strictly applicable to electrostatic instabilities involving non-relativistic dynamics of the plasma particles. We present the generalized relativistic theory[3] for the asymptotic pulse evolution of convective and absolute instabilities. This can be applied to electromagnetic instabilities in plasmas involving relativistic dynamics. We illustrate the theory by studying the pulse evolution for such instabilities in plasmas described by highly anisotropic distribution functions.

We assume an infinite plasma in a static uniform magnetic field, $\overline{B}_0$, with stationary ions and the unperturbed electron distribution function given by $f_0(p_\perp, p_\|) = \frac{\delta(p_\perp - p_{0\perp})}{2\pi p_{0\perp}}\delta(p_\| - p_{0\|})$ where $p_\perp$ ($p_\|$) is the momentum perpendicular (parallel) to $\overline{B}_0$. The space-time evolution of instabilities in electromagnetic waves that propagate along $\overline{B}_0$ ($\overline{k} \| \overline{B}_0$) and perpendicular to $\overline{B}_0$ ($\overline{k} \perp \overline{B}_0$) is examined. The dispersion relations for these waves are derived from the complete set of Maxwell's equations and the relativistic Vlasov equation. For $\overline{k} \| \overline{B}_0$ the asymptotic pulse shapes for the Whistler instability ($v_{ph} < c$; $v_{ph}$ is the phase velocity of the wave, $c$ is the speed of light) and the relativistic instability ($v_{ph} > c$) are presented. For $\overline{k} \perp \overline{B}_0$ the analysis for the pulse shapes is carried for electromagnetic instabilities with $\frac{k_\perp p_{\perp 0}}{m\Omega} < 1$ where $m$ is the electron rest mass and $\Omega$ the relativistic electron cyclotron frequency. The electromagnetic instabilities of the type considered may be of interest in the studies of: the generation of electromagnetic energy by relativistic electron beams; instabilities due to energetic electrons in ECRH, mirror-confined plasmas; and unstable radiations in space plasmas.

1. R. J. Briggs, Electron Stream Interaction with Plasmas, M.I.T. Press, 1964; A. Bers, "Space-Time Evolution of Plasma Instabilities – Absolute and Convective" in Handbook of Plasma Physics, Vol. 1, North Holland Publ. Co. (in press).
2. L. S. Hall, W. Heckrotte, *Phys. Rev.* 166, 120 (1968).
3. A. Bers, A. Ram, *Bulletin of the American Physical Society* 27, 919 (1982).

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# MHD AND ROTATIONAL STABILITY OF A QUADRUPOLE TANDEM MIRROR*

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We investigate the low mode number macroscopic stability of plasmas in the Phaedrus tandem mirror. Our stability analysis includes finite Larmor radius effects and $\vec{E} \times \vec{B}$ rotation. Starting with the low frequency, low mode number kinetic equations and considering only MHD type modes ($E_\parallel = 0$, $k_\parallel v_\parallel/\omega \ll 1$) a variational principle is formulated which is similar to the perturbed form of Newcomb's paraxial variational principle [1]. This variational principle is solved by expanding the modes in terms of a 3-D set of basis functions and solving for the coefficients by a Rayleigh-Ritz method. The quadrupole nature of the equilibrium is represented.

Despite the full 3-D representation of the modes and nonaxisymmetry of the equilibrium it is found that for values of $\rho_i/R_p > 0.05$ ($\rho_i$ -- ion Larmor radius, $R_p$ -- plasma radius), typical of present day tandem mirror machines, the most unstable modes are to a large extent (~ 98%) composed of a single poloidal Fourier (m) component. For Phaedrus the most unstable mode is an m = 1 rigid displacement. A general discussion of the degree to which a rigid displacement model is appropriate will be discussed.

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[1] W.A. Newcomb, Mirror Theory Monthly, Lawrence Livermore National Laboratory (Sept. 15, 1981).

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

Abstract submitted to
Sherwood Theory Meeting

1983

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Suggested Session:

Nuclear Physics in MFE

Polarized Fusion Reactions*. G. M. HALE and D. C. DODDER, Los Alamos National Laboratory--Interest in using nuclear polarization to modify fusion cross sections has been strongly revived by recent work[1] at the Princeton Plasma Physics Laboratory. Here, we present general results for polarized cross sections, derived from the density-matrix formalism[2] of nuclear scattering theory. Predictions are given for polarized d-T, d-$^3$He, and d-D fusion cross sections, based on our comprehensive R-matrix studies[3] of reactions in the four- and five-nucleon systems.

1. R. Kulsrud, H. Furth, E. Valeo, and M. Goldhaber, Phys. Rev. Lett. 49, 1248 (1982).

2. L. Wolfenstein, Ann. Rev. Nucl. Sci. 6, 43 (1956).

3. G. M. Hale and D. C. Dodder, Proc. Int. Conf. on Nuclear Cross Sections for Technology, Knoxville, 1979 (NBS Spec. Pub. 594), p. 650 (1980).

*Work supported by U. S. DoE, Basic Energy Sciences.

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# THE DYNAMO EFFECT IN LONG TIME REVERSED-FIELD PINCH DISCHARGES*

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The spontaneous reversal of the toroidal field in early pinch experiments, notably ZETA, gave rise to the idea that there must be an internal plasma mechanism of toroidal magnetic flux generation. This has become known as the Reversed-Field Pinch (RFP) "Dynamo Effect." This paper presents a combination of experimental and theoretical results that show how the "Dynamo Effect" manifests itself in a sustained way for power crowbarred ZT-40M discharges that last up to 20 ms.

By applying a toroidal voltage to ZT-40M the toroidal current can be slowly raised after the setup phase. The total toroidal flux is then observed to also increase so that the pinch parameter $\Theta$ $\left(B_\theta(\text{wall})/\langle B_z\rangle\right)$ remains approximately constant. For this to occur, negative toroidal flux must be expelled from the plasma since $B_z$(wall) remains negative. Although magnetic field profile data are not available, theoretical arguments show that there are strict limits on the amount of negative flux that can be present in the discharge after startup. These limits preclude explanation of the experimental observations without invoking the existence of a plasma mechanism that generates both positive and negative toroidal flux.

Utilizing the experimentally applied voltages as boundary conditions and the measured temperature, transport simulations are performed that indicate that the time scale for toroidal flux generation is short. It is shown that in 200-400 μs all initial negative toroidal flux is annihilated, and that in < 100 μs $B_z$(wall) in the simulations deviates significantly from that in the experiment. These results hold for ZT-40M whether the toroidal current is raised or held constant after startup. The simulations also show that in the presence of a large toroidal driving voltage, even unreasonably large temperatures at the toroidal field reversal point cannot explain the observed persistence of reversed toroidal field at the wall.

We conclude that the dynamo effect is active during the long time sustainment phase of the RFP. These studies indicate that the RFP configuration can be maintained indefinitely against resistive diffusion. There is no known theoretical limit to the RFP lifetime. Implications of the short timescale of the dynamo effect on theoretical stability and transport studies of the RFP are discussed.

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*Work performed under the auspices of the USDOE.

# Numerical Axial Stability Analysis for a Hot Electron Plasma in a Magnetic Trap*

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The stability of a high $\beta$ hot electron plasma is crucial to the development of the EBT and symmetric tandem mirror concepts. So far, the stability analysis of such a system is restricted to local approximation due to the complication of mirror equilibrium. Numerical procedures have been developed to solve the eigenmode equation for the low frequency ballooning-interchange/compressional Alfven modes in a self-consistent, high-$\beta$, long-thin mirror equilibrium. The Taylor distribution function[1] is assumed for all species (hot electrons, background ions and electrons). The finite-$\beta$ equilibrium is obtained by solving the perpendicular pressure balance equation with iteration on the curvature term (long-thin approximation). This equilibrium information is then used to determine the coefficients of the axial eigenmode equation, to be solved by a shooting method.

In a geometry such as that in a single EBT cell, the procedures described above recover the Lee-Van Dam stability boundary. The numerical result shows an abrupt transition to unstable region as the core beta increases for a fixed hot electron $\beta$, when the axial variation of the dispersion function, D, is artificially suppressed. However, taking into account axial variation poles in D may appear and lead to axial resonance. Consequently, the Lee-Van Dam boundary is smeared out. The system exhibits instability for all core beta and the growth rate increases as core $\beta$ increases.

Results for the symmetric tandem mirror will also be discussed.

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*Work supported by U. S. Department of Energy Contract No. DE-AC03-76-ET53057 with Science Applications, Inc.

[1] J. B. Taylor, Phys. Fluids 6, 1529 (1963).

# TOKAMAK DISRUPTIONS

J A Wesson
JET Joint Undertaking

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Disruptions can occur in a tokamak plasma in which there has been no perceptible change in the physical conditions. This leads us to ask what precipitates disruptions.

Earlier calculations showed that, while tearing mode island growth is normally stabilising, there are cases for which it is destabilising. This led to a study of saturated tearing modes and the discovery that, under conditions associated with disruptions, such saturated states did not occur.

These results are now interpreted in terms of the familiar $\Delta'$ theory in which the growth and saturation of the island width, w, are determined by the quantity $\Delta'(w)$. The calculation of $\Delta'(w)$ is changed to include the modification of the equilibrium resulting from the island itself. The new quantity is called $\Delta^*$ and the island size is given approximately by $\Delta^*(w)=0$. It is found that $\Delta^*(w)$ can have a minimum with respect to w. If this minimum is negative a saturated island exists. If disruptive conditions are slowly approached the minimum value passes through zero. A catastrophe is then reached and no saturated state exists. This results in rapid growth which leads to mode interaction and disruptive loss of confinement.

# Mode Induced Beam Particle Loss in Tokamaks*

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Large amplitude rotating magnetohydrodynamic modes have been observed to induce significant high energy beam particle loss during high power perpendicular neutral beam injection on PDX.[1] A Hamiltonian formalism[2,3] for drift orbit trajectories in the presence of such modes is used to study induced particle loss analytically and numerically. Resonant particle loss in the form of a beacon of ejected particles is found when the mode frequency equals the precession frequency. The loss mechanism is studied for various beam energies and injection angles. Significance for beam heating is discussed.

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

[1]K. McGuire et al., PPPL-1946 (1982), Phys. Rev. Lett. (1983).
[2]R. B. White, A. H. Boozer, and Ralph Hay, Phys. Fluids 25, 575 (1982).
[3]A. H. Boozer and R. B. White, Phys. Rev. Lett., 49, 786 (1982).

# ELMO BUMPY SQUARE*

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A new magnetics configuration based on the ELMO Bumpy Torus (EBT) confinement concept has been developed. The ELMO Bumpy Square (EBS) or ELMO Bumpy Racetrack (EBR) is formed by four or two bumpy cylinder sections (multiple magnetic mirrors) linked by sections of a high field toroidal solenoid of elliptic cross section. The EBS configuration (which is the focus of this work) localizes the unavoidable toroidal curvature in the corners of the square where its effects can be minimized by a magnetic field which is much stronger than the average field in the mirror sections. As in EBT, the central core plasma in EBS is stabilized by the presence of hot electron rings in the bumpy sections.

Detailed vacuum magnetic field and orbit calculations indicate that the single particle confinement, plasma centering in the magnetic field, and neoclassical lifetime in EBS are distinctly superior to those in a bumpy torus of comparable size. The hot electron rings, which are formed in sections of a bumpy cylinder, are exceedingly well centered about the magnetic axis. The core plasma pressure surfaces and the ambipolar potential should be better centered because toroidal effects in $\int d\ell/B$ occur in regions of high magnetic field. The fraction of transitional and passing particles (whose drift orbits are the least well-confined at high energies) is reduced by high "global" mirror ratio. In addition, these orbits are better centered than those in toroidal geometry.

A number of interesting heating techniques may be more practical in an EBS than in an EBT. Access at the corners permits a long path length for neutral beam injection, and lack of magnetic moment conservation at high beam energies should isotropize the hot ion distribution rather quickly. In an EBS that utilizes an EBT-S-like magnetic field ($\approx$1 Tesla) in the bumpy cylinder sections, slow wave ICRH and 60-GHz ICH can be launched from the corners with the rings sustained by 28-GHz second harmonic heating. Also, one is encouraged to speculate that launching localized electromagnetic waves (e.g., lower hybrid) in the corners might reduce neoclassical losses by scattering particles off poorly confined drift orbits and might reduce nonlinear effects of some types of instabilities as well.

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

# SELF-CONSISTENT CALCULATION OF RADIAL TRANSPORT IN TANDEM MIRRORS*

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The LLNL tandem mirror transport code[1] (TMT), which self-consistently calculates radial transport caused by quadrupole fields, has been used to address a number of physics issues important to the tandem mirror program: end wall potential control, simulation of the tandem mirror experiment (TMX), and quenching of radial transport.

In MFTF-B and tandem mirror reactor designs, end-wall potential control has been proposed as a method to reduce the radial electric field and hence central-cell radial transport and rotation drive. The code results indicate that a single plate of appropriate dimensions on the end wall can have an appreciable effect on the radial electric field over the bulk of the hot core plasma in the central cell.

Previous estimates[2] of resonant radial fluxes at the edge of the TMX plasma were lower than measured fluxes by about a factor of three. The addition of radial transport arising from ion-neutral collisions to the code model brings code results and TMX experimental data into good agreement.

Finally, the code has been used to test the prediction of quenching of radial transport.[3] As a coefficient pre-multiplying the diffusion coefficients is increased, the increase of radial loss rates may be mitigated (i.e., quenched) by a self-consistent flattening of density and potential profiles. Code results show that quenching is indeed important for intermediate values of this coefficient.

[1]Mirin, A.A., et al., submitted to Nucl. Fusion, LLNL Rept. UCRL-88287, 1983.
[2]Drake, R.P., et al., submitted to Phys. Fluids, LLNL Rept. UCRL-85872, 1981.
[3]Baldwin, D.E., and Logan, B.G., (eds.), LLNL Rept. UCID-18496, 1980.

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# TRANSPORT OF ROTATING TOKAMAK PLASMAS FROM GUIDING CENTER EQUATIONS*

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ABSTRACT

Recently, a collisional transport theory for a rotating plasma in an axisymmetric tokamak has been formulated[1] starting from the Fokker-Planck equation. In this formulation, a separation is achieved between a classical part having to do with gyromotion and a geometry-dependent part representing a generalization of the usual neoclassical theory. We have now found it possible to rederive the generalized neoclassical results in a much more straight-forward manner by starting from the usual drift-kinetic equation, performing the usual m/e expansion, but taking the self-consistent electric field to be one order lower, and hence larger, than usual. When in addition a singular perturbation on the mirror force and the electrostatic trapping effect arising from the centrifugal force is performed, all the results from a previous formulation[2] in the plateau to the Pfirsch-Schlüter basing on an expansion in the inverse aspect ratio are also reproduced. In the same regime, by using a set of newly derived matrix elements of the Fokker-Planck operator, we have numerically evaluated the transport fluxes for a pure plasma.

[1]Hinton, F. L., and S. K. Wong, Bull. Am. Phys. Soc. 27, 1127, 1982.
[2]Wong, S. K., and K. H. Burrell, Phys. Fluids 25, 1863, 1982.

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# CREATION OF HIGH ENERGY ELECTRON TAILS DUE TO THE MODIFIED TWO-STREAM INSTABILITY*

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Particle simulations of the modified two-stream instability demonstrate strong electron acceleration rather than bulk heating when the relative drift speed $v_d$ is below a critical speed $V_c$ . A very interesting nonlinear autoresonance acceleration process is observed by which the lower-hybrid waves accelerate the electrons much above the phase speed of the linearly unstable modes. Simple criteria are presented that predicts the value of $V_c$ and the number density of the accelerated electrons.

*Supported by ONR and NASA

HIGH-m TEARING MODE MAGNETIC TURBULENCE*

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ABSTRACT

Recent work on anomalous transport in low $\beta$ tokamaks[1,2] has emphasized non-linear mode coupling to explain the experimentally observed broad spectra. These calculations were restricted to electrostatic drift wave turbulence in which the electrons responded linearly. In high $\beta$ tokamaks, the non-linear current response (rather than charge accumulation) may be dominant and hence the electron nonlinearities become important. The simplest example of this situation is high-m tearing modes,[3,4] which have been previously considered retaining only wave-particle nonlinearities.[5] In the present work, we extend the analysis to include wave-wave non-linear coupling. The spectral intensity equations are derived and the implications for the saturated spectrum are discussed.

[1]Waltz, R. E., Phys. Fluids 26, (1983).
[2]Waltz, R. E., and R. R. Dominguez, GA Technologies Report GA-A16946 (1983).
[3]Rosenberg, M., et al., Phys. Fluids 23, 2022 (1980).
[4]Drake, J. R., et al., Phys. Rev. Lett. 44, 994 (1980).
[5]Dominguez, R. R., et al., Phys. Fluids 24, 472 (1981).

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# Transport Analysis in Small Stellarators*

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We present here the final results of our study on an L = 1, M = 3 Stellarator with a configuration commonly known as the HELIAC. The parameters of this device, whose construction has already been proposed by Princeton Plasma Physics Laboratory, are quite modest: major radius 1.4 m, plasma radius 0.2 - 0.7 m, magnetic field 1.2 T and plasma temperature 1 keV. Using a Monte-Carlo method[1,2] we have derived the ion diffusion coefficients by observing the times for half the number of marker particles to diffuse to the edge of the plasma. One such point for electrons has also been obtained showing that electron confinement is larger than ions by a factor of 12 without the presence of an ambipolar potential. A negative potential of around 4 times the thermal energy was found to make the ion and electron loss rates equal. The confinement time in this case is then around 10 msec.

[1] A. H. Boozer,and G. Kuo-Petravic, Phys. Fluids 24, 851 (1981).
[2] G. Kuo-Petravic, A. H. Boozer, J. A. Rome, and R. H. Fowler, J. Comp. Phys. (in press).

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

# A Radiated Power Interpretation of the Murakami Limit*

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In 1976, Murakami reported[1] that the maximum density in an Ohmically-heated tokamak scales as $B_T/R$. This work shows that the density limit results from impurity radiation losses exceeding ohmic heating input as the density increases. Our assumptions are that 1) both $Z_{eff}$ and radiation losses are determined by the concentration of a single impurity species, 2) a tokamak discharge must possess a factor-of-two range in electron temperature over which ohmic heating input exceeds radiative losses in order to exist, and 3) $q_o = 1$. The density limit then depends only on the impurity species and not on the impurity concentration. Use of current atomic physics data[2] results in a density limit

$$n_{max} = (1.5 \cdot 10^{13}\text{cm}^{-3})(B_T/1\text{T})(\frac{1\text{m}}{R})$$

for Fe, Mo, and W impurities. For a dominant O impurity, the density limit is three times higher. This represents quantitative agreement with Murakami's observations.

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

[1]M. Murakami et al., Nucl. Fusion 16, 347 (1976).

[2]D. E. Post et al., Atomic Data and Nuclear Data Tables 20, 397 (1977). Improvements to this data base have been incorporated.

# AN FRC FORMATION METHOD THAT DOES NOT RELY ON MAGNETIC FIELD LINE TEARING*

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Field reversed configurations (FRC) are normally generated in $\theta$-pinches when magnetic field line tearing at the $\theta$-pinch ends causes the inner-reverse bias flux lines to connect to the outer-forward bias flux lines, forming a closed configuration. The 2-D MHD code, MOQUI,[1] has been used to study an alternate FRC formation technique where the tearing process has been eliminated by using additional coils at the $\theta$-pinch ends to generate an initial cusp configuration. The field lines then form reconnected in the vacuum region instead of tearing in the plasma. Much more of the initial plasma inventory is swept in from the $\theta$-pinch ends, leading to a longer FRC equilibruim. Bekikov, et. al., at the Kurchatov Institute,[2] have reported very high energy efficiencies resulting from this formation method.

If no additional coils are used to delay the axial implosion, this formation method leads to a very fast axial implosion which has been observed to destroy the configuration in experiments. However, numerical calculations show that with the existing coil structure of the TRX-1 experiment,[3] the axial implosion can be delayed by as much as 5 $\mu$sec and be much more gentle. This is accomplished by carefully adjusting the bias current, triggering time, and forward bias in the trigger coil (which is between the $\theta$-pinch coil and the d.c. cusp/mirror coil) to produce an FRC which extends into a weaker field region near the ends of the $\theta$-pinch coil. The weak fields at the ends of the FRC lead to a very elongated equilibrium, however, the calculations show that this equilibrium is tearing unstable. Tearing usually occurs just inside the $\theta$-pinch ends. Therefore, the current in the trigger coils must be adjusted to rise sufficiently fast to trigger the axial implosion before tearing has time to start. The calculations also show that the initial preionized plasma density must be uniform beyond the ends of the $\theta$-pinch coil for the axial implosion to be delayed significantly.

1. R.D. Milroy and J.U. Brackbill, Phys Fluids 25,775 (1982).

2. V.V. Belikov, et al., "Keeping Down Losses in a Compact Torus With a Programmed Magnetic Structure Formation," 9th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, 1-8 September 1982.

3. J.T. Slough, A.L. Hoffman, and D.G. Harding, "Use of Controlled Reconnection to Generate FRCs with High Bias Flux," Proceedings of the Fifth Symposium on the Physics and Technology of Compact Toroids, Bellevue, WA (1982).

* Work supported by DOE Contract #DE-AC06-80ER53098.

# Neutral Beam Driven Impurity Flow Reversal in TFTR and FED/INTOR

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The NBI driven impurity flow reversal experiment in PLT[1] has been used to benchmark[2] a predictive model for impurity transport based upon Pfirsch-Schluter theory and the Stacey-Sigmar[3] theory for effects of beam momentum input and drags. These effects include modification of flows in the flux surface and of the radial potential gradient, as well as direct momentum input. The "benchmarked" model has now been applied to predict NBI driven impurity flow reversal effects in TFTR and in larger tokamak plasmas of the type suggested by the FED and INTOR conceptual designs.

When only the co-injected beams are used in TFTR, limiter-sputtered impurities are excluded from the inner half of the plasma, and the inward impurity flow in the outer half of the plasma is significantly reduced. The same model predicts a significant concentration of impurities in the center of the plasma when the co-injected and counter-injected beams are operated to produce no net toroidal momentum input. Operation of only the counter-injected beams results in the prediction of a rapid accumulation of limiter-sputtered impurities in the center of the plasma.

Application of the model to an FED/INTOR type plasma leads to the prediction that ~20-30 MW of 150-200 KeV NBI may suffice to significantly inhibit, although not prevent, limiter-sputtered impurities from entering the center of the plasma. This suggests that NBI (or rf) flow reversal might be used to achieve a "cold-radiating edge" and thereby limit sputtering erosion.

References:

1. D.R. Eames, PhD Thesis, Princeton Univ. (1980).

2. R.B. Bennett and W.M. Stacey, Jr., Bull. Am. Phys. Soc., 27, 1059 (1982).

3. W.M. Stacey, Jr. and D.J. Sigmar, Nucl. Fusion, 19, 1665 (1979).

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# SPECTRUM OF LOW-FREQUENCY, NON-AXISYMMETRIC OSCILLATIONS IN A COLD, CURRENT-CARRYING PLASMA COLUMN

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The spectrum of low-frequency, $m = \pm 1$ oscillations in a cold, collisionless, cylindrical plasma comprises the frequencies of the lowest radial eigenmodes and the surface modes of the fast magnetosonic wave, all the global eigenmodes of the Alfvén wave (ion cyclotron wave) and the Alfvén continuum. The spectrum of a homogeneous, currentless plasma cylinder is obtained from an analytical dispersion relation. This spectrum is compared with numerically obtained spectra of nonuniform plasmas with and without axial current. The connection of the MHD kink and internal kink instabilities with the global eigenmodes of the Alfvén wave is evidenced. Among all the modes of the magnetosonic wave which have frequencies in the Alfvén continuum, the ($m = -1$, $k < 0$)-surface mode is the best candidate for antenna-plasma coupling in an Alfvén Wave Heating scheme because its conversion layer is located well into the plasma interior.

# Poloidal Field Coil Design and Ideal MHD Stability of Bean-Shaped Plasmas*

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Recent Tokamak experimental results (high $\beta \sim 4.6\%$ in DIII; enhanced 'H' mode confinement with diverted plasmas in ASDEX, DIII and PDX) have enhanced the prospects for economically attractive Tokamak Fusion Reactor configurations. Recent theoretical studies show that bean shaped plasmas may permit very high $\beta$ (10-20%) Tokamak operation. Strong bean indentation improves ideal MHD stability by providing a stable path with increasing $\beta$ to the second ballooning stable region.[1] Beaning also has a stabilizaing effect on the internal kink mode,[2] which may be related to the fast ion confinement loss associated with the fishbone instability observed in PDX. However, obtaining bean-shaped discharges with practical coil systems is non-trivial, particularly as the required equilibrium vacuum field shape varies significantly with $\beta$ and bean indentation. The additional constraint on separatrix location for diverted discharge 'H' mode operation further complicates the problem. Within the constraints of PDX hardware, we have constructed sequences of fixed boundary equilibria with varying $\beta$ and bean shaping, for ideal MHD stability and vacuum field analysis. The equilibrium field is expanded as a combined series of moments and individual coil contributions for which a least squares fit is constructed. Free boundary equilibria are then generated using the resultant coil sets. From this and other constraints, a coil set will be selected which permits some flexibility with respect to bean shaping (particularly varying indentation) and a capacity for achieving high $\beta$ discharges. We will also report on isolated ideal MHD stability calculations for some of the equilibria, and initial results from a study on the existence of alternate asymmetric equilibria in beans.

*Work supported by U.S. DoE Contract No. DE-AC02-76-CHO-3073.
†Grumman Aerospace Corporation, Princeton, N.J.

[1] M. S. Chance *et al.*, this conference.
[2] J. Manickam *et al.*, this conference.

Ideal MHD Stability of Bean-Shaped Tokamaks*

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We investigate the ideal MHD stability of tokamaks with bean-shaped cross-sections. They are expected to yield stable equilibria at higher values of $\beta$ compared to the more conventional (circular and dee-shaped) cross-sections. The evidence in favor of ballooning (high n) stability is more explicit. The analysis of the low-n stability yields more complex results. We study the n=1 internal kink mode, low-n surface kink modes with vacua of finite and infinite extent surrounding the plasma as well as low-n internal ballooning type modes. With moderate 'bean-ness' the internal kink mode can be completely suppressed with $q_{axis}$ as low as 0.5. The low-n free surface modes tend to be the most unstable and are consequently of greater interest. At moderate indentation or bean-ness the mode is dominated by a global balloonlike nature, at large indentations a strong current driven mode manifests itself at low $\beta$. We vary the position and shape of an ideal perfectly conducting shell surrounding the plasma and show that complete stabilization is possible for reasonable shapes and further that these free boundary modes are also subject to second stable regions like the ballooning modes when the conducting shell is close by. Details will be presented.

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# DELTA RAY PRODUCTION AND STABILITY OF BEAM PROPAGATION IN HEAVY ION BEAM FUSION*

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The basic problems in HIB fusion concept are beam-plasma coupling characteristics and propagation stability of the beam through the chamber.[1] We study delta ray (secondary, tertiary, etc., electrons) production during the propagation of relativistic HIB in a background gas with pressures of 1-30 torr. Utilizing Monte Carlo simulation we study the influence of generated delta ray current (knock-on electrons current) on HIB propagation characteristics with emphasis on focusing by self-induced magnetic fields.

[1] K.A. Brueckner, Assessment of Drivers and Reactors for Inertial Confinement Fusion, Electric Power Research Institute, AP-1371, Research Project 1346-I. Palo Alto, CA (1980).
K.A. Brueckner and V. Stefan, Bul. Am. Phys. Soc. 27, No. 8, Part II, 1008 (1982).

*Work supported by DOE contract No. DE-AS08-81DP40195.

Kinetic Theory of Alfven Waves

S. M. Mahajan[‡] and J. E. Sedlak[‡‡], The University of Texas at Austin, Austin, TX 78712 - The well known magnetohydrodynamic continuum goes over to a discrete spectrum when electron parallel dynamics is included in the system. The special case of a Slab plasma with $k_{\parallel} = 0$ in the plasma, has been investigated.[1] We derive the appropriate equations for a current carrying inhomogoneous plasma in cylindrical geometry, and solve them to obtain the eigenfrequencies of the discrete spectrum for arbitrary $k_{\parallel}$. The theory unifies the study of modes below as well as within the magnetohydrodynamic continuum.

(1) J.W. Conner, W.M Tang, and J.B. Taylor, Phys. Fluids 26, 158 (1983).

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# "OMITRON": AN OHMIC-IGNITION TOKAMAK EXPERIMENT

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In order to achieve ohmic ignition in a tokamak device, a high enough value of the toroidal magnetic field must be provided, for a time long enough to allow for the ohmic heating of the plasma to take place to the desired extent. It is to be appreciated that the second requirement, concerning the duration of the pulse, is also of crucial importance, due to the unviability of superconducting solutions for producing the very high values envisaged for the toroidal field.

The key to ohmic ignition in a tokamak device lies therefore almost entirely with the toroidal magnet design. The conventional design of the toroidal magnet, which has been to a large extent optimized in recently proposed high field tokamaks, appears to provide parameters of magnetic field that are marginally insufficient for the attainment of ohmic ignition. A new, low-shear-stress (LSS) toroidal magnet design has however been elaborated (*), which seems to be suited to meet the requirements needed for ohmic ignition.

The above LSS toroidal magnet has been incorporated into the design of an ohmic-ignition tokamak called OMITRON. It is seen that also the problems associated with the transformer, which are usually quite severe in high field tokamaks, are in fact made easier by the considered design of the toroidal magnet. Numerical calculations, via the BERSAFE code, of magnetic and thermal stresses in the toroidal magnet of the OMITRON tokamak, have borne out the expectations concerning the mechanical performance of the envisaged magnet structure.

Standard transport and energy balance codes for tokamak plasmas indicate that the OMITRON parameters (field on axis 175 kG, major radius 40 cm, plasma aspect ratio 2.5, vertical elongation 1.5, effective pulse length at constant current 1.2 seconds, average plasma "beta" up to 4%) would even seem to guarantee a certain margin beyond what is required for the attainment of ohmic ignition. With somewhat larger values of the minor radius, aspect ratio and plasma "beta", there would also seem to be some chances of producing ignition conditions for the D-$He^3$ fuel and catalyzed D-D fuel, via an initial D-T burning trigger phase.

(*) Italian Patent Application No. 49482A/81 of October 14, 1981; U.S. Patent Application No. 433877 of October 13, 1982.

UCRL ABSTRACT
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# MODULAR COIL DESIGN AND MAGNETIC SURFACES IN HELIAC*

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The numerical procedure described in Ref. [1] is used to study various Heliac configurations. The calculation proceeds by computing the scalar potential, $\psi$, of a vacuum magnetic field, B, inside a given helical-toroidal vessel $\mathcal{D}$. Assuming that B = 0 outside $\mathcal{D}$, constant contours of $\psi$ coincide with the direction of the field generating surface currents which flow on $\partial\mathcal{D}$. The currents are strictly poloidal since $\psi$ is multiple valued in the toroidal angle. Once $\psi$, hence B, is computed the result is given to a field line integrator [2] which plots the magnetic surfaces and computes the transform.

This paper studies the effects that the aspect ratio, helical pitch, cross section, etc. have on field properties such as the magnetic well. Strong toroidal effects tend to give a shallow well. The aim is to find magnetic wells in configurations with large aspect ratio, where the helical effects dominate and which can be created with modular coils that encircle the torus poloidally.

The above procedure may be applied to traditional Stellarators in order to find modular coil configurations for that device.

[1] A. I. Shestakov and A. A. Mirin, Proc. Tenth Conf. on Numer. Sim. Plasmas, San Diego, Ca., Jan. 4-6, 1983.

[2] N. J. O'Neill and A. A. Mirin, TUBE, A Magnetic Field Line Tracer, LIBRIS Abstract P81, MFECC, Livermore, Ca.

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# COMPETING ATTRACTORS IN BUMPY TORI

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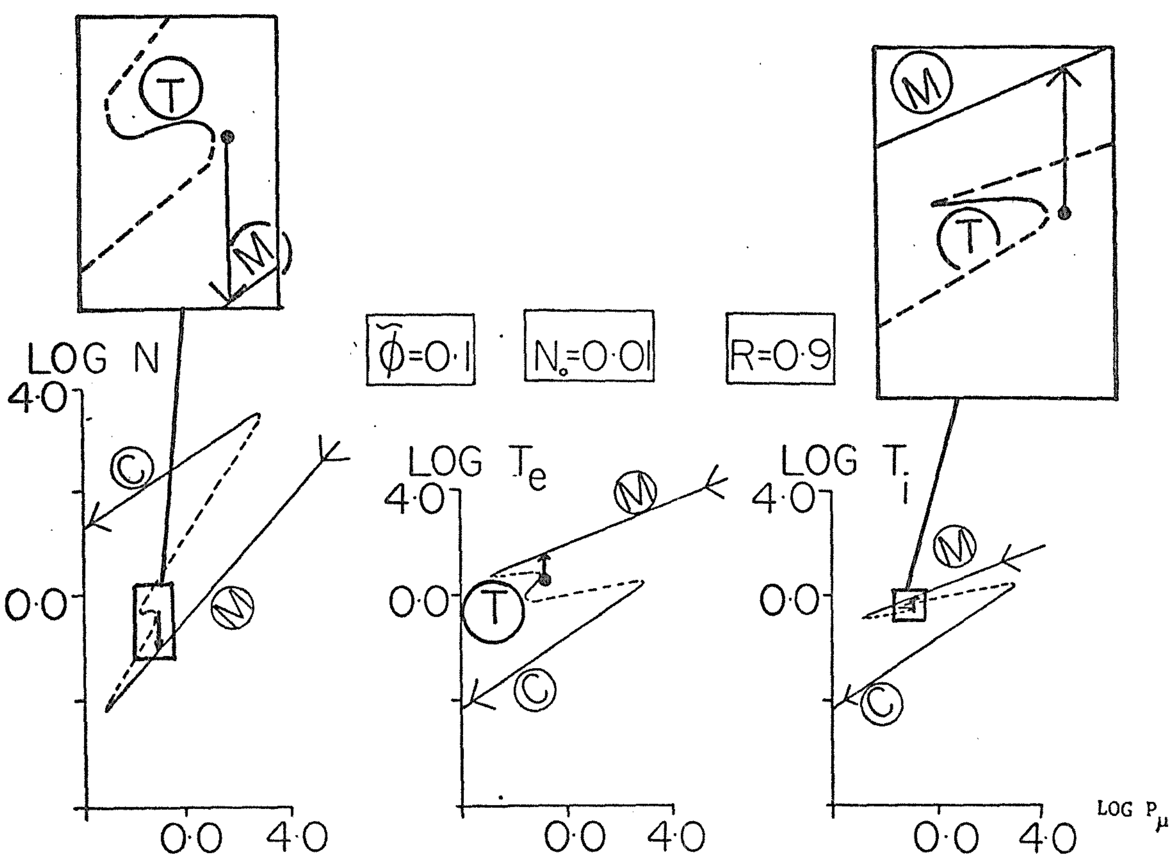
With the inclusion of ion cyclotron heating, the ambipolar potential has been seen to become less negative. If, under sufficiently powerful ICRH, the potential becomes positive we find the topology of the equilibrium surfaces for the point model equations with neoclassical nonresonant ions to be a complicated non-gradient dynamic version of the canonical cusp catastrophe. New folds emerge from degenerate equilibrium surfaces as the control vector (filling pressure, ...) is changed. More interestingly, we find strong sensitivity to small changes in initial conditions of the state variables (electron & ion temperatures, plasma density) which can drastically alter the final equilibrium state.



# Resonant Absorption at the Lower Hybrid Frequency

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## ABSTRACT

A new investigation of the absorption of the energy in a plasma at the lower hybrid frequency has been carried out using an approach similar to that used earlier in the theory of Alfven wave heating.[1] We assume the plasma to be described by the cold plasma equations for simplicity and choose a slab model in order to illustrate the theory. We consider a magnetic field constant in the z-direction but spatially varying in the x-direction; the slab is bounded by $-L \leq x \leq L$ and there is no variation in the y-direction. A staightforward linearization of Maxwell's equations gives the starting point for the theory. A Laplace transform in time, Fourier transforms in y and z allows combination of the differential equations to a form similar to those of ideal MHD. If we assume the special case of $k_z=0$, $k_y$ finite the governing equation for $E_y$, the y-component of the electric field becomes a second order ODE. A choice of the lower hybrid frequency with the further assumptions $\omega/\omega_{ci} > 1$, $\omega_{ce}/\omega > 1$ transform the governing equation for $E_y$ into the form

$$(f(\omega,x,k)E_y{}')' + G(\omega,x,k)E_y = 0 \qquad (1)$$

where f is a function which vanishes when $\omega^2 \to \omega_{pi}{}^2$. the ion plasma frequency. $G(\omega,x,k)$ is a complicated but nice function of its arguments. For boundary conditions we assume regularity at the origin and matching to an incoming wave away from the resonant layer defined as $x=x_r$ such that $\omega_{pi}{}^2(x_r) = \omega^2$. Equation (1) is identical in form to the governing equation describing the ideal MHD Alfven continuum and yields singular solutions about the resonant layer. We have borrowed much of the companion Alfven continuum analysis due to Tataronis[1] and have attempted to describe the energy absorption of "lower hybrid waves" without resorting to successive linear mode conversions[2] or dissipation processes. Still to be considered are two important aspects of the lower hybrid heating scheme: accessibility and matching.

This work was supported by the USDOE Contract No. DE-AC02-76ER03077.

1. J.A. Tataronis, J. Plas. Physics 13, 87-105, Feb. 1975.

2. S. Puri, M. Tutter, Proceedings of "2nd Internatl. Congress on Waves and Instabilities in Plasmas," Innsbruck, March 1975 (also IPP Report IV/82, March 1975).

# Finite-$\beta$ Effects on Drift-Wave Eigenmodes in Toroidal Plasmas*

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We have examined, both analytically and numerically, drift-wave eigenmodes in tokamaks including the effects of the finite-$\beta$ coupling to shear Alfvén waves. For toroidicity-induced eigenmodes, we find that finite-$\beta$ effect reduces the real frequencies but have little effect on the stability properties. Meanwhile, for the slab-like eigenmodes, finite-$\beta$ effects are found to not only reduce the real frequencies but also further stabilize the modes. Detailed parametric dependences will also be presented.

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# MODIFIED CAT-d FUEL CYCLES WITH OR WITHOUT TRITIUM ASSISTANCE

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Tritium assisted Cat-d fuel cycles[1-3] can improve fusion reactor power density, $P_f$, over that of Cat-d. These fuel cycles require tritium breeding. Using tritium assisted Cat-d, one finds that the tritium breeding ratio (TBR) approaches one rapidly with small increases in $P_f$.

An alternative way of improving the fusion power density, while maintaining plasma pressure, is by adjusting the $^3$He density in the plasma. The $^3$He density is adjusted, by controlling the reinjection fraction, to a level not exceeding that of the Cat-d plasma, and thus the fusion power density is optimized. The results of the study indicate that the fusion power density in the fuel cycle described above is relatively insensitive to the ion temperature. This allows one to use this fuel cycle at low plasma temperature. Other advantages of this cycle modification, in addition to improved power density, are that there are no requirements for tritium breeding or external $^3$He resources. These advantages lead to simplification of blanket design.

A tritium assisted variation of the above cycle has also been investigated. The $P_f$ in this case is also relatively insensitive to temperature, but the required minimum TBR rapidly approaches one as the power density increases. For example, if the TBR increases from 0 to 0.5, the power density improves by a factor of two. However, if the TBR increases from 0.5 to 0.99, the power density can improve by a factor of twenty to thirty.

Other optimized fuel cycles have also been investigated and will be presented.

[1]Conn, R. W., et al., "SATYR: Studies of a d-d Fueled Axisymmetric TMR," UCLA Report, PPG-S76, September 1981.

[2]Cohn, Daniel, Private communication.

[3]Gillegan, John, Private communication.

# Magnetic Field Effects on Ion-Electron Temperature Relaxation*

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The presence of a magnetic field can affect the energy transfer between ions and electrons when the electron gyro radius is less than the Debye length. Depending on the orientation of the impact parameter to the magnetic field, either an increase[1] or a decrease[2] in the energy transfer per collision can occur, compared to the classical no magnetic field case. A further complication in the analysis of the magnetic field effects arises from the wide range of electron speeds ($V_{th.-ion} \lesssim V \lesssim V_{th.-elect}$) that is involved in the temperature equilibration process with the ions. This makes the common approach that studies the effect on the "average" thermal electron unsuitable.

The approach taken here is to first evaluate the average energy-exchange rate of a test particle electron with Maxwellian ions, $\langle dE/dt \rangle_{e-i}$, using a previously desired collision operator[3] that includes the magnetic field effects. Then the equilibration power is found by averaging $\langle dE/dt \rangle_{ei}$, which includes the magnetic field effects at each speed, over the actual electron distribution. This approach differs from previous studies[1,4,5] in that it retains the magnetic field effects at each speed rather than concentrating on the effect on the average thermal electron. A consequence is that the equilibration power is found to be affected by the magnetic field at lower field strengths than previously thought possible. In particular, it is found that there is a net increase in the equilibration power of up to $\lesssim$ 20% for $T_i/T_e < 2$, $B \lesssim$ 100kG, and $n_e \sim 10^{14}$ cm$^{-3}$.

## References

1. V. P. Silin, JETP, 16, 1963, 1281; Sov. Phy. Tech. Papers, 14, 1969, 589.

2. J. R. McNally, Jr., Nuc. Fusion, 15, (1975), 344.

3. M. H. A. Massan, C. J. H. Watson, Plasma Physics, 19, (1977), 237.

4. S. Ichimaru, M. N. Rosenbluth, Phys. Fluids, 13, (1970), 2778.

5. D. Baldwin, C. J. Watson, Plasma Physics, 19, (1977), 517.

* Work supported by US DOE DEAC02 76ET52040.

# STUDY OF ECRH PROFILE CONTROL ON THE STABILITY OF RESISTIVE TEARING MODES*

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ABSTRACT

The effect of plasma profile modifications by ECRH on the stability of resistive tearing modes is investigated. The application of ECRH to tokamaks results in both heating and current drive, which leads to local temperature and current profile modifications. We investigate the effect of ECRH-induced profile changes on the stability of the linear and nonlinear development of the tearing mode, and on the behavior of sawtooth oscillations. This is done for relevant tokamak parameter regimes, using transport model simulations which include ECH, and MHD stability codes. The possible control of disruptions via proper ECRH profile control is explored quantitatively.

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# HOT PLASMA DECOUPLING CONDITION IN BUMPY CYLINDER GEOMETRY*

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Recently, the hot plasma decoupling condition between the low frequency hot electron interchange mode and the interacting core pressure-driven interchange has been of interest. This condition influences the critical values of $\beta_c$ and $n_{Hot}/n_{core}$ required for stability. Quantitative evaluations of this condition for EBT devices have been carried out both analytically and using radially-dependent shooting codes only in simplified slab geometries localized near the midplane at the hot electron ring position. Decoupling criteria have also been derived for a bumpy cylinder model which involve field-line weightings of the various core and hot plasma equilibrium parameters. Evaluations of the decoupling conditions will be made in the more realistic bumpy cylinder geometry using a 2-D finite $\beta$ equilibrium code.

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# BOUNCE AVERAGED CALCULATION OF ICRF INDUCED ION SLIDEAWAY/FUSION REACTIVITY ENHANCEMENT*

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A toroidal electric field E increases the tail population of ions due to runaway in the effective electric field E* = E (1-Z/ZEFF), thereby giving enhanced reactivity in a fusion plasma(1). The additional application of RF power results in a larger runaway rate, further increasing reactivity(2). These effects are studied with a new, 2D in velocity space, bounce averaged Fokker-Planck/RF quasilinear diffusion code(3). Reactivity enhancement relative to an equivalent Maxwellian plasma is computed for cases with E-field only, RF only, and both effects combined. The assumed RF field is representative of ICRF waves for minority fundamental, second and third harmonic heating, in a D-T plasma.

(1) H. P. Furth and P. H. Rutherford, Phys. Rev. Lett. Vol. 28, 545 (1972).

(2) Z. G. An, Y. C. Lee and C. S. Liu, Univ. of Maryland Report PL#81-013 (1980).

(3) G. D. Kerbel and M. G. McCoy, 1983 Sherwood Theory Meeting.

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

# HYBRID SIMULATIONS OF FIELD REVERSED SYSTEMS*

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The hybrid code CIDER is being used to study axisymmetric field reversed systems maintained by large Larmour radius ion rings. This work involves two aspects of the problem. Firstly we present latest results of the simulation of the build-up to field reversal. Earlier work[1] was concerned with the situation where a weak beam was slowly injected. This showed how a toroidal magnetic field is developed, and was consistent with another simulation of an FRC.[2] Latest simulations reveal that at reasonable electron temperatures $T_e \sim 1$ eV, good field reversal is difficult to achieve. The field reversal region remains small and the code ultimately goes unstable. In order to obtain a fully field reversed system the magnetic Reynold's number had to be reduced to order unity. The second aspect concerns field reversal enhancement by the injection of a weak ion ring into a pre-existing equilibrium. Previously the code RINGA was used to simulate the problem.[3] We are now using CIDER which has the added physics of electron dynamics and toroidal magnetic field. We will present preliminary results of the weak ion ring injection simulations.

*Work supported by U.S. DOE Contract DE-AS02-76ET53065.

†Present address: Science Applications Inc., 1710 Goodridge Drive, McLean, VA 22101.

[1] P.M. Lyster, R.N. Sudan, Bull. Am. Phys. Soc. 27, 1111 (1982).

[2] D. Hewett, 1982 Sherwood Meeting (Sante Fe, New Mexico) Poster 1C26.

[3] P.M. Lyster, R.N. Sudan, 1982 Sherwood Meeting (Sante Fe, New Mexico) Poster 3C38.

Resistive Effects on the Shear Alfvén Wave in Tokamaks*

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According to ideal MHD theory for inhomogeneous equilibria, the shear Alfvén wave exhibits a localized, non-zero time-averaged growth at locations in the plasma where the wave frequency of an external source is equal to the local shear Alfven resonance frequency. However, Kappraff and Tataronis[1] demonstrated that the inclusion of a finite but small plasma resistivity in a slab model results in the formation of a dissipative layer about the resonance locations, thereby leading to a saturation of the wave amplitude. In this study, we consider the effects of resistivity on the shear Alfvén wave in an axisymmetric tokamak geometry. The plasma dynamics are described by a set of resistive MHD equations in which the effects of finite plasma pressure are retained for the equilibrium only. By retaining the effects of finite resistivity only in a narrow boundary layer about the resonance location, the structure and saturation amplitude of the shear Alfvén wave can be determined.

*Work supported by the National Science Foundation under Grant ECS-8110038.

[1] J.M Kappraff and J.A. Tataronis, J. Plasma Physics 18 ,209 (1977).

# Construction of Coils for Three-Dimensional Vacuum Fields Such as Stellarators*

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A. Shestakov and A. Mirin[1], have shown that the three-dimensional Laplace equation solution could be utilized to find closed stellarator-like configurations. The author would like to point out that the closed coil system could be constructed arbitrarily close to any stellarator configurations provided that there exists a closed magnetic surface between the outermost magnetic surface and the coil system used to construct the stellarator configuration. The practical applications of this theorem would be modularization, improving the coil utilization factor, and so on.

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

1. A. Shestakov and A. Mirin, this conference.

# CALCULATION OF THE MERCIER CRITERION FOR STELLARATORS

O. Betancourt and P. Garabedian

The Mercier criterion for stability of local modes has been incorporated in our code for the calculation of magnetohydrodynamic equilibria with nested flux surfaces. The parallel current is evaluated so as to achieve good accuracy. The criterion decomposes into three blocks of terms representing contributions from shear, from a magnetic well, and from a Schwarz inequality related to island width. The latter contribution becomes unfavorable even at zero pressure in cases with significant magnetic islands. We find that the Mercier criterion is easier to compute than the growth rates of global modes. It has been used to assess Heliotron E, Wendelstein VII-A, ATF-1 and heliac configurations. Numerical examples will be presented.

# Ion Transport in EBT-S*

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A model has been developed to simulate both bulk and tail ions for typical EBT-S operating parameters. In this model the guiding center trajectories are followed numerically using a model magnetic field and a parabolic ambipolar potential. The shape of the loss region in velocity space has been determined for a variety of initial starting locations. The passing and nearly passing ions are lost when the kinetic energy is much greater than the potential well depth. At lower energies the loss region encompasses nearly all particles which are slightly more energetic than the confining potential. Finally, ions with a kinetic energy less than the electrostatic potential are generally confined. Scattering due to coulomb collisions has been incorporated in this model by a statistical representation of the Fokker-Planck collision operator which accounts for both pitch angle and energy scattering. Measurements of the bulk ion confinement time, $\tau_b$, have been made by measuring the lifetime of an ensemble of test ions which have initial energies on the order of 2-5 eV. For a potential depth $\varphi_o = -250$ V the confinement time was found to be in excess of 200 ms. The confinement time of high energy isotropic tail ions, $\tau_h$, has been measured as a function of the initial energy, $E_o$. Assuming $\varphi_o = -250$ V the scaling of $\tau_h(E_o)$ is proportional to $E_o^{-.93}$, which suggests that the loss of tail ions scales with the drift time and that $\tau_h$ is dominated by convective losses. The variation is actually slower than $E^{-1}$ due to the fact that the loss region in velocity space widens at lower energies, and due to the increasing scattering rate. Since the confinement of ions initally loaded on closed drift surfaces is substantially longer than ions on open drift surfaces it is most likely that the tail ions are anisotropic unless nonadiabatic effects result in isotropization on a timescale faster than $\tau_h$. Estimates of this time are currently being made. Assuming that the hot ions have a Maxwellian distribution with temperature $T_h$, the scaling of all tail ions is found to be $\tau_h = 51.5/T_h$ (ms). These measurements of $\tau_b$ and $\tau_h$ suggest that the tail ions escape so quickly that even a small population of tail ions dominates the ion flux and leads to an ambipolar potential which is of the order as the experimental results. The scaling of the self-consistant potential as a function of the tail to bulk ion concentration is determined by a global flux balance. Currently the role of multiple charge exchange is being investigated as a means of tail formation. Simulations of sputtered $Al^{+2}$ impurity lifetimes will also be presented.

*Work supported by TRW Fellowship Grant
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# COMPUTATIONS OF PLASMA RESISTIVITY IN THE PRESENCE OF A REVERSED-FIELD PINCH DYNAMO*

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Three techniques for estimating plasma resistivity in a Reversed-Field Pinch (RFP) are discussed. These expressions are: 1) the local plasma resistivity on the magnetic axis ($\eta_{eff}$) as computed with azimuthally symmetric plasma models, Faraday's law and empirically given boundary fields; 2) the global plasma resistivity based on energy balance and time averaged plasma models ($\eta_{\parallel}^{w}$), and 3) global plasma resistivity based on magnetic helicity instead of energy balance ($\eta_{\parallel}^{k}$). For a series of 190 kA shots on ZT-40M these resistivities had the following approximate relationships on axis; $\eta_{\parallel}^{k} \simeq 2/3\ \eta_{\parallel}^{w} \simeq 1/3.5\ \eta_{eff}$. We account for this substantial range in resistivity estimates as follows: 1) $\eta_{eff}\ J|_{r=0} = E_z|_{r=0}$ is a poor estimate of resistivity because the RFP dynamo is not explicitly represented in the expression; 2) $\eta_{\parallel}^{w}$ includes an anomally factor representing power required to drive plasma fluctuations, approximately one-third of the total power input for the shots examined; 3) $\eta_{\parallel}^{k}$ is the best global estimate of RFP plasma resistivity; some reasons for this shall be discussed. Several plasma current and temperature profiles are examined to give a range of $\eta_{\parallel}^{k}$ values. This range of $\eta_{\parallel}^{k}$ agrees within a factor of two with the Spitzer resistivity computed from Thomson scattering temperature data taken on ZT-40M.

*Work performed under the auspices of the USDOE.

# Equilibrium Calculations with Stellarator Expansion Techniques*

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Major progress has been made in calculating stellarator equilibrium properties by introducing a stellarator expansion in which behavior in the multipolar field structure is incorporated analytically, reducing the problem to a two-dimensional one for the lowest-order, axisymmetric flux function.[1-4] Different predictions of the magnetic axis shift have been found using these programs from those obtained by introducing a subsequent large-aspect-ratio-expansion[5] into the stellarator expansion equations. These differences have been interpreted as arising from nonlinear terms[3,4] in the displacement vector $\xi$ which measures the axis shift. A meaningful explanation of the lack of observation of the predicted singularity[5] at very low $\beta$-values for systems with small aspect ratios is that the shift of the axis provides an average magnetic well, destroying the resonance character of the homogeneous part of the equilibrium equation. We are attempting to establish a connection between this explanantion and the interpretation based on the nonlinear behavior.

*Work supported by U.S. DoE Contract No. DE-ACO2-76-CHO-3073.
†On loan from Westinghouse R & D Center.

[1] J. M. Greene and J. L. Johnson, Phys. Fluids 4, 875 (1961).
[2] G. Anania, J. L. Johnson, and K. E. Weimer, PPPL-Report 1945 (Nov. 1982).
[3] L. M. Kovrizhnykh and S. V. Shchepetov, Sov. J. Plasma Phys. 7, 527 (1981).
[4] V. D. Pustovitov et al., 9th Int'l. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, Maryland, Paper IAEA-CN-41/V-5 (1982).
[5] J. L. Johnson, J. M. Greene, and K. E. Weimer, Plasma Phys. 8, 145 (1966).

# Dependence of Axis Shift on the Pressure Profile in an $\ell$ = 2 and the Optimized WVII-AS Stellarators

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A critical equilibrium beta of $\langle\beta\rangle \simeq$ 1.5% was estimated [1] for the optimized WVII-AS stellarator by using a bell shaped pressure profile $p = p_0[1-(r/a)^2]^2$ ($\langle\beta\rangle \simeq \beta_{ax}/3$) and applying the flux-conserving code by Bauer, Betancourt, Garabedian [2a]. In order to make an estimate of a critical equilibrium beta in that study, the radial axis shift was limited to b/2 which is half of the minor half axis of the standing ellipse. Compared to a pure $\ell$=2 stellarator the displacement is reduced by a factor of about two. At small $\langle\beta\rangle$-values the shift is linearly proportional to $\langle\beta\rangle$. A similar study has been done for a parabolic pressure profile $p = p_0[1-(r/a)^2]$ ($\langle\beta\rangle \simeq \beta_{ax}/2$). As shown in Fig. 1 the critical equilibrium $\langle\beta\rangle_c$ is increaed to 2.4% for the parabolic pressure profile if the axis shift is limited to b/2 and increases to about 4.5% if a large relative axis shift of $\xi$=0.45 is allowed. The flux surface contours are shown in Fig. 2 for $\langle\beta\rangle \simeq$ 5%. A weak saturation behavior can be observed which might be presumably due to the wall being rather close to the magnetic axis at the place of the standing ellipse and the flux conserving model. (A more realistic simulation would require the solution of the free boundary value problem including a surrounding vacuum region.) These above results should be compared to those obtained by running the equilibrium code BETA [2b] in a nonfluxconserving (but no net toroidal current) mode.

A similar study about the effect of the pressure profile has been done and results have been cmopard to those by the CS-code [3] for a high-shear $\ell$=2,4 configuration whose global characteristics in twist number ($t_{ax}\simeq$0.28, $t_b\simeq$0.79), shear, and number of field periods (M=10) are close to the parameters of the ATF-1 device.

[1] F. Herrnegger, Z. Naturf. 37a (1982) 879.
[2a,b] F. Bauer, O. Betancourt, P. Garabedian, A Computational Method in Plasma Physics, Springer-Verlag, New York, 1978; and Paper at this meeting.
[3] R. Chodura, A. Schlüter, J. Comput. Phys. 41 (1981) 68.

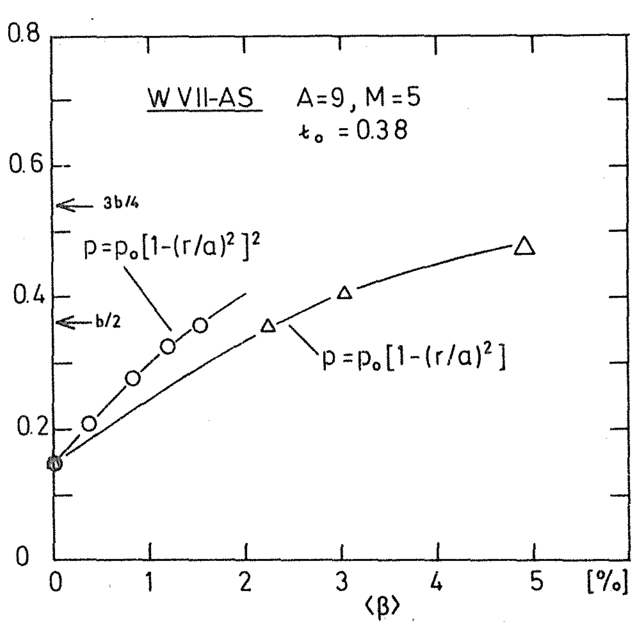


Fig. 1 (left). Axis shift (extrapolated in mesh size) vs $\langle\beta\rangle$.

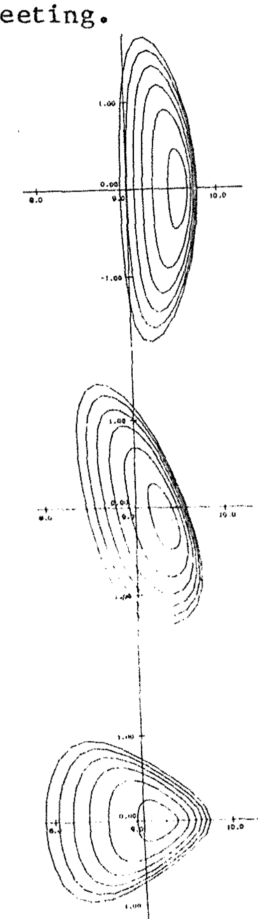

Fig. 2 (right). Flux surface contours of WVII-AS (extrapolation to zero mesh size): $\langle\beta\rangle \simeq$ 0.05, parabolic pressure profile.

Finite-Bandwidth Effects on Lower Hybrid Current Drive*

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Recent experimental results[1] have shown that when the density limit is reached at which current generation ends, sidebands appear in the wave spectra monitored at the plasma edge. This spectral broadening has been attributed to parametric processes. In order to study what effect a multi-wave spectrum has on the current drive process, we have performed a number of computer simulations with an electrostatic particle code[2] which follows the dynamics of a large number of particles self-consistently.

The electron velocity distribution along the magnetic field $B_o$ is chosen to have a long tail in one direction before the RF is turned on. Five waves are launched with frequencies centered about the lower hybrid frequency $\omega_{LH}$, separated by half the ion cyclotron frequency $\Omega_i$. Because the phenomena is now governed by the interference among the various waves (which is periodically reproduced every $4\pi/\Omega_i$) one can see the competing tendencies of the current to relax by electron-ion collisions and to increase due to the lower-hybrid waves. When the interference brings the net wave amplitude below a certain level, collisional relaxation dominates and the current decays. As the net electric field increases, current generation is observed.

*Work supported by U.S. Department of Energy Contract No. DE-AM03-76SF0010 PA 26, Task VI B

1. F. C. Jobes, et al, Bull. of A.P.S. 27, 1069 (1982).

2. V. K. Decyk, G. J. Morales, and J. M. Dawson, Proc. of the Third Joint Varenna-Grenoble Intl. Symp. on Heating in Toroidal Plasmas, Grenoble, France, 1982, Vol. II, p. 517.

# DRIFT WAVE TURBULENCE IN TOROIDAL GEOMETRY*

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## ABSTRACT

Recently we have applied resonance model DIA numerical methods[1] including both wave-wave and wave-particle nonlinear effects to calculate the spectral intensity for drift wave density fluctuations $I_{k_x k_y k_\parallel \omega}$ $[\tilde{n}/n = (\rho_s/L_n)I^{1/2}]$ in a three dimensional sheared slab geometry.[2] Among other results, we found the parallel correlation lengths to be rather long $\partial I_k/\partial k_\parallel / I_k \sim O(10)L_n$, which suggested that toroidal coupling effects from the ion curvature drift should be included. The shear ($k_s = 1/L_s$) induces linear coupling between adjacent k modes, since $k_x$ and $k_\parallel$ become operators when acting on $I_{k_x k_y k_\parallel}$[3]:

$$\hat{k}_x = k_x - \frac{ik_y k_s}{2}\frac{\partial}{\partial k_\parallel} \quad ; \qquad \hat{k}_\parallel = k_\parallel + \frac{ik_y k_s}{2}\frac{\partial}{\partial k_x} \quad .$$

These appear as $\hat{k}_x^2$ and $\hat{k}_\parallel^2$ in the ion polarization drift and ion sound terms of the dispersion relation. When curvature drift is added, $\omega_*$ is replaced by the total drift frequency

$$\omega_*\{1 - \frac{2L_n}{R}\left[\cos\left(\Theta - \frac{1}{2}\frac{i}{Rq}\frac{\partial}{\partial k_\parallel}\right) + \frac{\hat{k}_x}{k_y}\sin\left(\Theta - \frac{1}{2}\frac{i}{Rq}\frac{\partial}{\partial k_\parallel}\right)\right]\}$$

and $I_k$ becomes a function of $\Theta$, the poloidal location [$\Theta = O(\pi)$ for outside (inside)]. Arbitrarily high order $k_\parallel$ derivations now appear in the dispersion relation. We show how this rather simple extension of DIA methods to toroidal geometry based on a physical observable $I_k(\Theta)$ can be derived from the standard ballooning representation for the nonlinear amplitude equations.[4]

[1]Waltz, R. E., Phys. Fluids 26, 1983.
[2]Waltz, R. E., and R. R. Dominguez, GA Technologies Inc. Report GA-16946, 1983 (see BAPS 27, 944, 1982, 2Q2).
[3]Similon, P, Doctoral Thesis, Princeton University, 1981.
[4]Frieman, E. A., and L. Chen, Phys. Fluids 25, 502, 1982.

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# SOME ANALYTIC APPROXIMATIONS TO FOKKER-PLANCK MIRROR-LOSS CONSTANTS*

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Some simple analytical forms are derived which can be useful in estimating the scaling of mirror end losses in the limit of low mirror ratio or for sources injecting at other-than-normal incidence with respect to the magnetic field lines. For the former, a variational principal can be used; for the latter a special separated form of the inhomogeneous Fokker-Planck equation can be employed. Comparisons with other forms and with Fokker-Planck computer code results will be given.

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# SIMULATION OF INERTIAL AND BEAM DRIVEN EFFECTS ON IMPURITIES IN ISX-B*

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Experiments on beam-heated ISX-B plasmas indicate that counter-injection leads to enhanced accumulation of impurities[1] and coinjection leads to reduced accumulation of impurities[2] relative to ohmic heated plasmas. Both inertial[3] and beam-driven[4] effects can modify impurity distributions in beam-heated plasmas, and we have attempted to simulate the effects of counterinjection on an intrinsic iron impurity[1] using the inertial effect alone.[5]

We now have implemented a treatment of beam-driven effects in our basic impurity transport simulation code, IMPTAR, and present here simulation results for both coinjected and counterinjected plasmas with inertial and beam-driven effects treated both separately and together. These results indicate that for plasmas with ion density and temperature gradients comparable to those observed in ISX-B: (1) impurity distributions even in ohmic heated plasmas are modified by the inertial effect, (2) the inertial effect alone qualitatively could account for the enhanced impurity accumulation observed in counter-injected plasmas, and (3) using existing theory, neither the inertial effect alone nor a combination of it and beam-driven effects qualitatively can account for the reduced accumulation observed in coinjected plasmas.

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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.

[1]R. C. Isler, E C. Crume, and D. E. Arnurius, Phys. Rev. A 26, 2105 (1982).

[2]R. C. Isler et al., submitted to Nuclear Fusion.

[3]K. H. Burrell, T. Ohkawa, and S. J. Wong, Phys. Rev. Lett. 47, 511 (1981).

[4]W. M. Stacey and D. J. Sigmar, Nucl. Fusion 19, 1665 (1978). 27, 1060 (1982).

[5]E. C. Crume, S. P. Hirshman, R. C. Isler, and D. E. Arnurius, Bull. Am. Phys. Soc. 27, 1060 (1982).

# SIMULATING TURBULENT CONVECTION*

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A spectral analysis of turbulent convection that includes small length scales has been set up for numerical simulation. The nonlinear coupling to and ultimate viscous damping of the shorter wavelengths are approximated by coupling an exact discrete set of modes to a Kolmogoroff-like continuum using 'Direct Interaction Approximation' methods[1-2] for straddling the boundary. We address numerical questions caused by finite density gradients and aliasing, and present preliminary results for a two-dimensional 'Navier-Stokes' approximation[3] of the anelastic MHD equations.

*Work supported by NASA Contract NAGW-90.

[1]R.M. Kulsrud, R.N. Sudan, Comments Plasma Phys. Contr. Fusion 7, 42 (1982).

[2]R.N. Sudan, D. Pfirsch, submitted to Phys. Fluids.

[3]E.K. Maschke, B. Saramito, 1982 Int. Conf. Plasma Phys. (Goteborg, Sweden, 1982).

# Simulation of Mode Coupling Equations for Drift Waves in Axisymmetric Tokamaks*

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Using the nonlinear gyrokinetic equations, we have derived a set of nonlinear mode coupling equations for strong drift wave turbulence in axisymmetric tokamaks. In deriving the mode coupling equations, ballooning mode formalism is employed, ion parallel dynamics are retained, and dissipative trapped electron destabilizing effects are properly included. Imposing outgoing wave energy boundary conditions, this set of equations should represent nonlinear drift wave dynamics in realistic geometries. An initial value code has been developed by employing a predictor-corrector scheme. Linear dynamics of the drift waves (toroidicity-induced modes and slab-like modes) have been confirmed with the eigenmode analysis.[1,2] Preliminary nonlinear calculations show energy cascading to the small toroidal mode number modes as well as reductions of ballooning structure of the modes. More detailed results will be presented.

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

[1] L. Chen and C. Z. Cheng, Phys. Fluids 23, 2242 (1980).

[2] C. Z. Cheng and L. Chen, Nucl. Fusion 21, 403 (1981).

# PARTICLE CONFINEMENT SCALING IN A FIELD-REVERSED CONFIGURATION

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The particle confinement time in a field-reversed configuration is derived, and is found to have a Bohm-like scaling of the form $\tau_N \propto r_s \ell_p / D_B$, where $r_s$ and $\ell_p$ are the separatrix radius and length, respectively, and $D_B$ is the Bohm diffusivity. The coefficient of proportionality is composed of two parts, one representing the closed line region. The closed line factor is proportional to $\langle\beta\rangle\langle T\rangle/(\beta_s T_s)$ where the subscript s indicates the value at the separatrix, and $\langle\ \rangle$ is the cross-section average. The open line factor is simply $\rho_{io}/\ell_s$, where $\ell_s$ is the effective sheath thickness and $\rho_{io}$ is the ion gyroradius in vacuum at the separatrix temperature. Experimental and theoretical evidences are presented to show that $\rho_{io}/\ell_s$ is always comparable to unity. This confinement law clarifies the approaches to improved confinement in a field-reversed configuration. These include larger $r_s/r_c$ ($r_c$ is the coil radius) which reduces $\beta_s$, larger $r_s$ which may reduce both $\beta_s$ and $T_s$, and reduce endloss rate on open field lines.

# EBT PLASMA PERFORMANCE WITH IMPROVED REFUELING MODEL*

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Previous studies of plasma performance in EBT-P and EBT-Q using the ORNL Radially Resolved Time Dependent One-Dimensional Transport (RRTDOT) code[1] have assumed arbitrary particle sources. Refueling by pellet injection[2] has now been incorporated in RRTDOT. The extrapolation to a reactor-sized plasma is shown, along with preliminary analysis of the effects of density source profile shaping.

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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.

[1]E. F. Jaeger, C. L. Hedrick, and L. A. Berry, Bull. Am. Phys. Soc. 27, 1086 (1982).

[2]W. A. Houlberg, M. A. Iskra, H. C. Howe, and S. E. Attenberger, ORNL/TM-6549 (1979).

# EQUILIBRIA WITH SINGULAR CURRENTS IN TOKAMAKS*

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## ABSTRACT

Toroidal equilibria with locally concentrated currents on rational surfaces are used to simulate tokamak discharges. These singular currents are assumed to be superimposed on an otherwise axially symmetric toroidal equilibrium. Phase locked singular current distribution on neighboring rational surfaces can reasonably account for experimentally observed stationary rotating plasma. The resultant magnetic configuration and its effect on angular momentum transport through a resistive wall is discussed.

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# Stability Studies Using the Stellarator Expansion*

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The PEST equilibrium and stability programs have been modified[1,2] to incorporate the stellarator expansion. With this large-aspect-ratio expansion, the effect of the nonaxisymmetry in the field is treated analytically, and the problem is reduced to a two-dimensional one. Application has only been made to stability studies with respect to modes with small values of the toroidal and poloidal mode numbers where diagonalization of the kinetic and potential energy matrix elements is straightforward. We have modified the codes so as to evaluate the Mercier criterion which provides insight into localized modes. Comparison of these localized criteria with the potential energy $\delta W$ for lower mode number modes shows good agreement. We have also modified the axisymmetric ballooning mode code to incorporate the stellarator expansion model. This is straightforward, because the effective magnetic field is given in terms of the poloidal flux in the same manner as in the PEST axisymmetric formulation and the effective field-line curvature is given by

$$\underset{\sim}{\kappa} = -\frac{1}{2}\nabla\Omega; \qquad \Omega \equiv \langle B_\delta{}^2\rangle/B_o{}^2 + 2(r/R)\cos\theta.$$

*This work supported by U.S. DoE Contract No. DE-AC02-76-CHO-3073.
†On loan from Westinghouse Research and Development Center.

[1]G. Anania, J. L. Johnson, and K. E. Weimer, Princeton PPL Report-1945 (November, 1982) to be published.
[2]G. Anania and J. L. Johnson, Bull. Am. Phys. Soc. 27, 1022 (1982).

# CROSS-FIELD FREE ELECTRON LASER*

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We consider stimulated emission of electromagnetic radiation from electrons moving in uniform applied electric $\hat{\underset{\sim}{x}}E_0$ and magnetic fields $\hat{\underset{\sim}{z}}B_0$, and a plane-polarized wiggler magnetic field $\hat{\underset{\sim}{x}}B_w \sin k_0 y$. The electrons are accelerated to relativistic velocities in the $\hat{\underset{\sim}{y}}$ direction due to the $\hat{\underset{\sim}{x}}E_0 \times \hat{\underset{\sim}{z}}B_0$ drift. The cold, fluid equations are then used to determine the linear growth rate in the tenuous beam limit. Although planar geometry is assumed, these results can be used to model FEL stability properties in a large-aspect-ratio rippled-field magnetron.[1]

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[1]G. Bekefi, Appl. Phys. Lett. 40, 578 (1982).

# RUNAWAYS AND CURRENT DRIVE

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An interpretation of the density limit, observed in recent lower-hybrid-wave current-drive experiments, is proposed. It is argued that the runaways resulting from an initial or residual Ohmic electric field play a crucial role in the phenomenon.

The mechanism of runaway-current sustainment by lower-hybrid waves, as proposed by C.S. Liu et al. (Phys. Rev. Lett. 48, 1479 (1982)), is re-examined. It is shown that, for realistic range of parameters, this mechanism does not allow a significant current to be sustained.

A highly modular, finite-element code, aimed at weak turbulence studies in magnetized plasmas, is being developed. Presently test are being performed for the classical electron runaway problem. The numerical method seems to suffer from errors known to occur in the solution of the standard multidimensional advection-diffusion equation.

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# ROLE OF 2nd HARMONIC ($\omega = 2\omega_c$) ECRH IN MAINTAINING A TANDEM MIRROR THERMAL BARRIER*

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The formation of thermal barriers by ECRH in tandem mirrors is studied using a multi-region Fokker-Planck code, a test-particle simulation code, and analytic modelling. The calculations include fundamental heating ($\omega = \omega_c$) near the axial potential maximum and second-harmonic heating ($\omega = 2\omega_c$) near the midplane. It is found that second-harmonic heating alone can feed and sustain the hot-electron population for TMX-U parameters in the steady state. This result is valid for either of two sources of cold electrons -- a Maxwellian stream or an actual escaping distribution from the central cell. With the latter, more realistic cold electron source, the end loss escaping from the ECRH heated plug cell is predominately hot electrons with energies $\sim$ 10-20 keV. The role of the fundamental heating is to control the magnitude of the ion-confining potential. The power required at the fundamental ranges from 0 to $\sim$ 30% of that at the second harmonic. An analytic expression for the scaling of the confining potential is obtained from the solution to a simplified Fokker-Planck problem which models ECRH diffusion and pitch-angle scattering.

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# EQUILIBRIUM AND STABILITY PROPERTIES OF "BEAN" SHAPED PLASMAS*

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Work which has shown increased stability to internal ideal MHD modes if an indentation is placed on the inside of a conventional D-shaped plasma[1,2] (generating a "bean" shape) has led to experimental interest in building or modifying tokamak devices to generate such shapes. This interest has motivated a more complete study of the stability properties (both resistive and ideal) of such plasmas.

Two sequences of equilibria were generated in which the shape was characterized by $\delta_B$=b/a (b is the distance from the major axis to the inside edge of the plasma at the midplane minus the distance from the major axis to the extreme inside edge of the plasma, with a the distance across the plasma at the midplane). Each sequence varied $\delta_B$ from 0 (D shape) to 0.26 (strong bean shape). For one sequence the safety factor at the edge was allowed to vary (from 1.6 to 2.75; $q_o$=.7) with $I_p$ (plasma current), $B_T$ (toroidal field), $V_p$ (plasma volume) and $\overline{\beta}$ (toroidal average $\beta$) kept fixed. For the other sequence, the safety factor profile was fixed (q=.7 to 2.75) with $I_p$ varied. Again $B_T$, $V_p$ and $\overline{\beta}$ were fixed at the above values.

Ideal MHD stability studies were done with the compter code ERATO[3] (for low n modes) and MBC[4] (for large n). Initial results confirm internal mode stabilization with increasing $\delta_B$. However, for external modes an increase in $\delta_B$ results in significant destabilization. Both sequences had $\delta_B$=0 equilibria which were stable to n=0 axisymetric modes. In contrast, the $\delta_B$=.26 equilibrium common to both sequences was unstable with an inverse growth rate of ~100μ sec. This mode could be stabilized, however, with a perfectly conducting wall near the plasma.

For internal resistive modes, the code RST[5] was used. Stabilization increased with $\delta_B$ for both sequences. The effect was much greater, however, when the q profile was fixed. This is due to the increase in rational surfaces in the plasma when $\delta_B$ was increased and $I_p$ was held fixed. This increase in rational surfaces partly masks the stabilizing effects of the shaping being studied.

Details of the above and additional results will be shown.

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†Computer Sciences at Oak Ridge National Laboratory.

1R. L. Miller and R. W. Moore, Phys. Rev. Lett. 43 (1979) 765.

2C. Mercier, Proceedings of the Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion, Innsbruck, Austria (1978) Paper no. IAEA CN-37-P3-2.

3R. Gruber et al., Comp. Phys. Comm. 21 (1981) 323.

4R. Moore, "M.B.C., A Ballooning Stability Code for Finite Toroidal Mode Number," General Atomic Report GA-A16243 (1981).

5V. E. Lynch, B. A. Carreras, H. R. Hicks, J. A. Holmes and L. Garcia, Comp. Phys. Comm. 24 (1981) 465.

# MONTE CARLO STUDY OF ECRH IN TOKAMAK PLASMAS*

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ABSTRACT

A Monte Carlo code was developed to study ECRH in toroidal geometry. The rf effect is incorporated into the particle guiding center motion through the multiple time expansion. Strong asymmetry in energy increase is observed when the resonant surface is placed at the low field side as compared with that at the high field side, making heating more effective for resonant surface at the low field side. The oposite appears to be true at the initial stage because of rf energy on trapped electrons is weaker. Pitch angle scattering and rf field strength are important in controlling the trapped population in the nonlinear stage. Neoclassical effects on heating and current drive, as well as comparisons with experiments, will be discussed.

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# INTEGRAL EQUATION SOLUTION TO MAGNETIC COMPRESSIONAL MODE

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The magnetic compressional mode, which in EBT is driven by hot electron diamagnetism, is susceptible to instability if the background density is too large. Analytic analysis is tractable if the grad-B drift dominates the curvature drift. However, for a moderate diamagnetic well, this inequality need not apply and an integral equation must be solved. We have set up the eigenmode expressions, using the high bounce frequency limit, to solve the integral equation. Substantial variations from the analytic solution is observed when grad-B and curvature drifts are comparable. Stability boundaries as a function of various parameters will be presented.

Work supported by U.S. Department of Energy Grant DE-FG05-80ET 53088.

# Axisymmetric MHD Equilibria with Flow

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ABSTRACT

Ideal MHD equilibria with flow are computed for axisymmetric tokamak configurations. Following the analysis of Ref [1] the resulting differential equation is of the same type as the Grad-Shafranov equation, if the flow is purely toroidal. A perfect conducting wall at the given surface is imposed as boundary condition. We apply the Galerkin method in conjunction with two dimensional finite elements. In the iteration of the solution of the nonlinear elliptic equation the elements are adopted to coincide with flux surfaces yielding the equilibrium in flux-coordinates. This procedure is expected to work also well for divertor-type equilibria with stagnation points directly at the surface. The presented results display the accuracy of the code as well as its fast execution.

[1] E. Hameiri, Phys. Fluids 26, 230 (1983)

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# Analytical Investigations of Effects of Resistive Interchange Turbulence on Energy Confinement in Reversed-Field Pinch

Z. G. An and P. H. Diamond Institute for Fusion Studies, The University of Texas at Austin, Austin, TX 78712. - Recent computational investigations[1] have indicated that electron conduction losses due to magnetic flutter produced by resistive interchange instabilities may have a significant effect on energy confinement in a reversed-field pinch. Here analytical investigations of this confinement deterioration mechanism are reported on.

Using approximate analytical solutions of the (compressible) MHD equations for even and odd potential parity slow and fast resistive interchange modes[2], mixing length theory is used to estimate the potential and magnetic perturbation turbulence levels. These results are used to calculate the stochastic magnetic field diffusion coefficients for weak[3] and strong magnetic turbulence. An expression for the anomalous electron thermal conductivity is then derived for various regimes. Special attention is focused on the region between the core and field-reversal point.

The effect of kinetic modifications to MHD stability results and predicted confinement scalings are discussed. Preliminary results from considerations of the effects of self-consistent inclusion of conduction losses in the stability analysis, and of the effects of such losses on the maintenance of field-reversal, will be discussed.

(1) T.C. Hender and D.C. Robinson, IAEA-CN-41/I5
(2) J. Finn and W. Manheimer, Phys. Fluids 25, 4, (1982).
(3) A. Rechester and M. Rosenbluth, P.R.L. 40, (1978).
Supported by DOE grant DE-FG05-80ET 53088.

# Adiabatic Compression and Translation of the S-1 Spheromak Plasma*

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A modification to the S-1 spheromak experiment is proposed to demonstrate adiabatic compression of the spheromak plasma.[1] If the major radius is decreased a factor of c by a self-similar compression, the number density and temperature should increase by the factors $n_e \sim c^3$ and $T \sim c^2$. Thus a compression factor of $c \leq 2$ can lead to order of magnitude increases in confinement time.

We investigate the relative merits of two variations in which (1) the plasma is translated into a burn chamber and then compressed, and (2) the plasma is continuously compressed as it is translated from the formation to the burn chamber. A modified version of the 2-D spheromak formation code[2] is used to model the compression and translation.

*Work supported by U.S. DoE Contract No. DE-ACO2-76-CHO-3073.
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[1]M. Katsurai and M. Yamada, Nucl. Fusion 22, 1407 (1982).
[2]S. Jardin and W. Park, Phys. Fluids 24, 679 (1981).

# A POSSIBLE MECHANISM FOR MASS FLOW GENERATION IN REVERSED-FIELD PINCHES*

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Recently[1] a possible mechanism for the generation of mass flow in Reversed-Field Pinches was proposed in an attempt to explain the observed[2] high apparent group velocities of line density disturbances in ZT-40M. It is shown that mass flow in an annulus of at least several cm can result from plasma-wall interaction due to thermal momentum transfer to the wall by finite Larmor radius ions. Recent work substantiates the theoretical conjecture numerically. Using a two-dimensional hybrid code (fluid electrons, particle ions)[3] it is shown that the outer plasma edge develops a mass flow of the order of the ion thermal speed, directed antiparallel to the toroidal plasma current, in agreement with theory. The width of this moving edge region is consistent with previously obtained quasilinear estimates.

1. J. P. Mondt, Los Alamos National Laboratory Report LA-9682-MS, January 1983.

2. A. R. Jacobson and M. G. Rusbridge, Los Alamos National Laboratory Report LA-9589-MS, November 1982.

3. D. W. Hewett, J. Comp. Phys. 38, 378 (1980).

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# Suppression of the m=2 Rotational Instability in the Field-Reversed Configuration

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## ABSTRACT

The factor limiting the lifetime of compact toroid plasmas formed in field-reversed configuration (FRC) experiments generally has been the appearance of the m=2 rotational instability. We examine this instability with a 2 1/2D quasineutral hybrid (particle ions, fluid electrons) simulation code.[1] The method was chosen because the field null in the FRC makes a fully kinetic treatment of the ions critical, since simpler models such as finite Larmor radius fluid theory do not give a correct description of the FRC rotational instability.[2] We present two methods for suppressing this instability. The first method is based on reducing plasma rotation and the second is by the application of multipole fields.

Our simulations show that rotation due to particle loss leads to lower spinup rates than predicted by rigid rotor models, because of the development of velocity shear near the separatrix. The velocity shear persists until the appearance of an instability that carries the rotation through the field null into the bulk of the plasma. The m=2 rotational instability is not observed until after the bulk of the plasma is rotating. By forming equilibria with increased values of S and $x_s$ simulations show that the time for the bulk of the plasma to rotate may be significantly increased, hence increasing the length of time prior to the onset of the m=2 rotational instability.

Hybrid simulations demonstrate that the m=2 rotational instability in the FRC can be suppressed by the addition of a multipole component to the magnetic field after the formation phase. We initialize rotationally unstable rigid rotor equilibria and then apply an external quadrupole field, which is linearly increased until it reaches a desired maximum amplitude. We find that the instability can be suppressed without stopping the plasma rotation for levels of quadrupole field comparable to those used in recent experiments at Osaka in which the m=2 instability was not observed.[3] This result is also consistent with current experiments on FRX-C at Los Alamos which exhibit stable lifetimes several times longer than previous results without the multipole field.[4]

1. D.S. Harned, J. Comput. Phys. 47, 452, (1982).
2. D.S. Harned, Phys. Fluids, to be published.
3. T. Minato et al., Proc. of Ninth IAEA Conf. (1982).
4. R.K. Linford, private communication.

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**Plasma Edge Turbulence**

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Near the edge of most torodial plasmas, where the plasma temperature is below a few tens of eV, the mean free path of electrons becomes comparable to or shorter that the major radius. In this regime, collisional damping of electrons (rather than collisionless damping) becomes the driving mechanism of the drift wave turbulence. However, the electron collision rate may be assumed to be sufficiently small such that the electron temperature variation along the direction of the ambient magnetic field may be negligible. We derived model mode coupling equations which describe nonlinear resistive drift wave properties in such a regime and solved them numerically to study the property of turbulence near a plasma edge. The wave number spectrum of the turbulence is found to inversely cascade from a peaked spectrum in the azimuthal direction and to isotropize to form the two dimensional Kolmogorov spectrum in large wave number regimes, $k^{-3}$. The frequency spectrum is found to be much broader than the drift-wave frequency even for a fixed value of wave number. For most plasmas, it was found that the turbulence property can be described primarily only by one parameter, $\kappa$ which is the measure of the density gradient normalized to the ion gyro-radius at the electron temperature. In particular, the fluctuation energy and the particle flux across the magnetic field are found to be linearly proportional to $\kappa$. This leads to the Bohm type particle diffusion with $(\delta n/n)^2 \simeq 6\kappa$. The numerical results have good agreements both qualitatively as well as quantitatively with experimental results obtained at the scraping layer of tokamaks. Implications of the results on the H-mode operation of a tokamak will also be discussed.

# STEEPEST DESCENT MOMENT METHOD FOR THREE-DIMENSIONAL MHD EQUILIBRIA*

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An energy principle is used to obtain numerical solutions of the MHD equilibrium equation $\vec{J} \times \vec{B} - \nabla p = 0$ for nested, three-dimensional toroidal magnetic surfaces which are expressed in the inverse coordinate representation $\vec{X} = \vec{X}(\rho,\theta,\zeta)$. Here $p = p(\rho)$ labels a magnetic surface, $\vec{B} \cdot \nabla\rho = 0$, and $\theta$ and $\zeta$ are poloidal and toroidal flux coordinate angles, respectively. The equilibrium solutions consist of the set of Fourier coefficients (known as moments) appearing in the doubly-periodic spectral decomposition of $\vec{X}$. These moments, which are functions of $\rho$ alone, are shown to satisfy a coupled system of non-linear, second order ordinary differential equations in $\rho$. A steepest descent iteration is developed for solving this system efficiently whenever a significant number of moments ($\gtrsim 4$) is needed to accurately represent the equilibrium. The existence of a positive definite energy functional guarantees monotonic convergence of this iteration toward an equilibrium solution (in the absence of magnetic island formation). A renormalization of the poloidal angle $\theta$ is introduced to insure the rapid convergence of the Fourier series for $\vec{X}$, while simultaneously permitting satisfaction of the MHD requirement that magnetic field lines should be straight in flux coordinates. This method is used to obtain equilibria for rippled tokamaks, and its application to stellarator configurations will be discussed.

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# THEORY OF H-MODE DISCHARGES IN DIVERTED TOKAMAKS*

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ABSTRACT

Recent experiments in ASDEX and Doublet III have shown the existence of an H-mode with good confinement in neutral beam heated plasmas with a divertor. Motivated by these observations, we propose here a theory of the plasma behavior in the divertor channel and scrape-off layer. In the case of relatively low energy and particle flow to the divertor plate, the main energy loss is through the electron heat conduction along the channel. As the energy and particle fluxes exceed certain values due to the increased injected neutral beam power, the plasma flow in the divertor channel is enhanced. As this enhanced flow slows down, either due to formation of a shock or drag by colder ions from the plate region, an electrostatic potential minimum develops to inhibit the electron conduction, i.e., a thermal barrier is formed. This, along with the mirror containment of the trapped ions in the scrape-off layer, helps to raise the plasma temperature at the edge. This hotter edge plasma is more stable against various resistive modes, and thus is less turbulent. With the line tying action of the plate, there is also less convection. Fluid and kinetic equations are solved to substantiate this model and regions of low and high modes in the parameter space of Mach number versus collisionality are delineated.

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# SCALE-VARIANT FRACTALS AND PLASMA COLLISIONS: THE TRUTH ABOUT CLASSICAL TRANSPORT*

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If $\Lambda = n\lambda_D^3$ denotes the number of particles in a Debye sphere, then the expected microscopic electric field $\vec{E}_{coll}$ seen by a particle is, in magnitude, of order $E_o \sim \Lambda^H (e/r_{min}\lambda_D)$ and, in direction, random. The parameter H satisfies $0<H<\frac{1}{2}$ with its deviation from the value $\frac{1}{2}$ a measure of the interactive antipersistence of the random walk associated with the building up of $\vec{E}_{coll}$ by successive addition of electrons and ions to the Debye sphere (cf. fractional Brownian motion). The conventional Fokker-Planck formulation erases this isotropic microscopic field by averaging over the statistics of the two-body vector increment rather than the vector sum, and so only the much weaker anisotropic field $\vec{E}_{drag}$ due to particle motion survives. Note that $E_o/E_{drag} \sim \Lambda^{1+H}/\ell n\, \Lambda \gg 1$. The usual averaging procedure rests upon the principle that a moving particle visits many Debye spheres $(N \sim \omega_p t)$ and so the randomly oriented $\vec{E}_{coll}$ cancels out. However, the particle must visit enough Debye spheres for this cancellation to occur; indeed, a simple argument shows that $|\vec{E}_{coll}(t)| \sim E_o/\sqrt{\omega_p t}$. Hence, for $|\vec{E}_{coll}(t)| \lesssim E_{drag}$, one requires that $t \gtrsim \omega_p^{-1}\Lambda^{2+2H}/(\ell n\Lambda)^2$ for the random isotropic field to be truly negligible. <u>For shorter experimental lifetimes, it follows that the conventional Fokker-Planck formulation is inappropriate</u> and thus a fundamental reassessment of collisional processes in such experiments is called for. The important role of scale-variant fractals in a more careful analysis of the microscopic electric field $\vec{E}_{coll}$ is explained and some of the far-reaching consequences of this new insight are assessed.

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

# NONLINEAR REDUCED FLUID EQUATIONS FOR TOROIDAL PLASMAS*

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Systems of nonlinear equations are derived from the Braginskii fluid equations to describe low frequency resistive modes in a finite $\beta$ toroidal plasma. The most general system consists of five coupled equations for density, electron temperature, velocity stream function, flux function, and parallel velocity. However, simpler systems can be derived for special cases, in particular resistive MHD. These equations are distinguished from the standard[1] reduced resistive MHD equations in two respects: first we have included previously neglected effects such as average favorable curvature and compressibility which are known to be important in the linear theory of resistive modes.[2] These effects enter when one considers modes whose characteristic growth time is much longer than the shear Alfvèn time. Second, we have included all relevant electron diamagnetic terms which have been found to stabilize linear tearing modes in high temperature plasmas.

The case of global (low n) modes in a large aspect ratio low $\beta(\beta_p \sim 1)$ torus and the case of local (high n) modes in an arbitrary $\beta$, arbitrary aspect ratio torus will be considered separately.

1. H. R. Strauss, Phys. Fluids 20, 1354 (1977).
2. A. H. Glasser, J. M. Greene, and J. L. Johnson, Phys. Fluids 18, 875 (1975).

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

# UNIVERSAL IDEAL-MHD BETA SCALING LAW*

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## ABSTRACT

We have derived simple scaling laws for the ideal-MHD $\beta$ limits as a function of plasma shape parameters (inverse aspect ratio $\varepsilon$, elongation $\kappa$, and triangularity $\delta$). $\beta$ limits ($\beta_c$) are obtained by optimizing the current profile to all n-modes. If no wall stabilization is assumed, high-$\beta$ experiments in ISX-B, PDX, and Doublet III all exceed the $n = 1$ kink mode limit. Thus we are led to include realistic stabilization mechanisms such as when the presence of a cool mantle and wall stabilization, which may occur the characteristic real frequency of the kink is greater than the inverse resistive diffusion time of the vacuum vessel. Then, the kink limit is above the $n = \infty$ ballooning mode limit when the safety factor at the plasma surface, $q_s$, is greater than 2. Even with a close wall, the kink is still unstable when $q_s < 2$. We postulate a universal ideal-MHD scaling law which combines the hard $q_s = 2$ limit of the kink with the ballooning limit for $q_s > 2$:

$$\beta_c = 0.16 q_s^{-1.26} \varepsilon^{1.1} (1 + 2\varepsilon^2) \kappa^{1.2} [1 + 0.5(\kappa - 1)^2](1 + 1.5\delta) \quad ,$$

$$q_s > 2 \quad , \qquad \beta_c = 0 \quad , \qquad q_s < 2 \quad .$$

This law shows that triangularity is almost as important as elongation to reach high $\beta$ values and predicts that the highest $\beta_c$ obtained at $q_s = 2$ is limited by ballooning modes. $\beta_c$ values in excess of 20% have been obtained for the Big Dee geometry under these conditions by optimizing both plasma shape and current profile ($\varepsilon \sim 2.5$, $\kappa \sim 2.3$, indented shape on the inside edge). Such high $\beta$ values make the use of advanced fuels attractive.

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# COMPARISON OF EBT EXPERIMENTAL RESULTS WITH A NEOCLASSICAL MODEL OF ELECTRON TRANSPORT*

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A point model[1] of EBT particle and power balance is used to compare experimental measurements of electron density and temperature in EBT with a neoclassical theory of electron transport. The model is semiempirical in that the quantity $e\phi/T_e$ is treated as a parameter consistent with the experimental observation that this quantity is roughly constant in the range of present operation. The observed scaling of electron density and temperature, and thus of energy confinement, from soft x-ray measurements, where extensive published data is available, agrees well with neoclassical predictions. Thomson scattering measurements indicate lower values of electron temperature than the soft x-ray values by a factor of 1/3-1/2. In this case the model predicts a different scaling. For given $\phi$ the lower $T_e$ results tend toward lower values of neutral density and longer confinement time. Though the published (1981) Thomson scattering data is far less extensive than the soft x-ray data, no apparent correlation with neoclassical theory is evident. Recent experiments[2] suggest the discrepancy may be due to diagnostic problems in the 1981 Thomson scattering results.

*Work supported by DOE under contract no. DE-AC01-82ER53126.

[1] C. L. Hedrick, unpublished.

[2] ORNL, private communication.

# EBT RING CREATION AND CONTROL BY FREQUENCY-MODULATED MICROWAVES*

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We propose a new method to create and control EBT rings by utilizing frequency-modulated 2nd harmonic ECRH heating. The method would shine the microwave pulse on electrons which are deeply trapped at the minimum magnetic field region in the EBT geometry. As the electrons are heated, we reduce the microwave frequency such that exact frequency resonance is maintained with the 2nd harmonic of the relativistically correct electron-cyclotron frequency. In this manner the electrons which are roughly phase-matched initially with the microwaves can be heated to a high temperature coherently in a one swing to form an electron ring. Advantages of this method in comparison with the conventional method are as follows: (a) control of the radial ring location and axial length ($T_\perp >> T_\parallel$), so that the ring volume can be minimized; (b) a final ring temperature below the nonadiabatic limit, reducing the nonadiabatic energy leakage as well as synchrotron radiation loss; (c) energy absorption efficiency of almost unity, even with 2nd harmonic ECRH, giving more efficient use of the microwave power.

Once the rings are created, they can be maintained by either repeating the frequency-modulated ECRH pulses at some appropriate time interval or applying low power fixed frequency microwaves to compensate the ring energy loss as well as some particle loss.

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# PARAMETRIC GENERATION OF ELECTRON AND ION RINGS IN EBT

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We investigate the possibility of electron and ion rings generation in EBT by nonlinear heating processes.[1] A new mechanism is proposed based on quasilinear interaction[2] of parametrically excited waves with plasma electrons and ions. If the established turbulence level in the short wave length region is higher than the Dreicer field, a process of effective linear momentum transfer (in addition to energy transfer during heating by relatively longer wave length excitations) takes place. Another possibility is in the interaction of parametrically excited waves with ions and electrons in the regions of lower density after being convected away from the resonance region. A ring power balance analysis is given showing conditions under which these mechanisms are effective.

[1]N. A. Krall and V. Stefan, this conference.

[2]V. Stefan and V. T. Tikhonchuk, Phys. Rev. Lett. 98, 1976 (1982).

# ANOMALOUS ABSORPTION AT ELECTRON AND ION CYCLOTRON HARMONICS IN ELMO BUMPY TORUS

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Anomalous absorption processes that can take place during electron or ion cyclotron resonance heating of Elmo Bumpy Torus[1] are studied. We study parametric excitations of electron ($n\Omega_e$, $n = 1,2,\ldots$, $\Omega_e$-electron cyclotron frequency) and ion ($m\Omega_i$, $m = 1,2,\ldots$, $\Omega_i$-ion cyclotron frequency) cyclotron waves coupled to lower hybrid and ion-acoustic waves. Special attention is given to parametric decay into two electron or ion Bernstein modes. Threshold analyses for a variety of excitations, taking into account convection and inhomogeneity, are given. For ECR we invoke a cascading[2] saturation mechanism, while for ICR we invoke induced scattering on ions and electrons. We compare turbulence levels with results of linear theory and discuss the significance of anomalous absorption processes in contemporary EBT experiments.

[1]N. A. Krall, "A Perspective on EBT Electron Ring Theory," Proceedings of the 2nd Hot Electron Ring Physics Workshop, Vol. 1, December 1-3, 1981, San Diego.

[2]V. Stefan and A. Bers, Phys. Fluids (to be published).

# PROSPECTS FOR ACHIEVING IGNITION IN HIGH-FIELD TOKAMAKS

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We have analyzed the prospects of achieving ignition in high-field tokamaks. Scenarios utilizing ohmic heating, or with the addition of ICRF or compressive auxiliary heating, are discussed. We consider all of the currently popular scaling laws for tokamak transport. The sensitivity of ignition to the assumed transport scaling is examined using the INESCO parametric systems program. For each scaling, a family of buildable and ignitable tokamaks is examined.

Discharge ontogenies are simulated with the DDMAK transport code. The transport model in this program includes switches for the transport scaling, flux-line reconnection modeling of tearing-mode and sawtooth activity, and ripple diffusion. Impurity effects, non-local alpha deposition, ash buildup, and self-consistent plasma-limiter interactions are included. Transport models are used for synchrotron radiation and interactions with neutrals. These simulations demonstrate that current penetration, density buildup, and impurity and ash accumulation are all tractable in proposed experimental scenarios. They support, with sophisticated plasma modeling, the systems program analyses of the ignitability of specific tokamak designs.

# LOSS CONE INSTABILITIES IN THE TARA ANCHOR CELL*

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Ion loss cone instabilities (ALC and DCLC) have been examined in model equilibria for the anchor cell of the TARA tandem mirror, by numerically solving the axial eigenmode equation with outgoing wave boundary conditions at the mirror throats, using WKB across the field lines. The equilibrium includes fanning of field lines, a self-consistent axial density profile of warm plasma confined between the transition region and potential peak, and a stream of unconfined warm plasma flowing out from the central cell. The eigenmode equation includes ion cyclotron harmonics with finite resonance width. The stream density needed for stability was calculated for various field lines and orientations of $\underline{k}_{\perp}$. This was done for both a hot ion anchor and a hot electron anchor, both with and without a "belly band" coil (which produces a small bump in the magnetic field around the midplane). Two classes of modes were found: 1) ALC modes, with $\underline{k}_{\perp}$ oriented the short way across the fan near the outer mirror throat. These modes were most unstable near the axis, being little affected by the density gradient, and required stream densities of about 2% for stability in the case of the hot ion anchor (at $\beta_i$ = 4.3%), and about 1% for the hot electron anchor ($\beta_i$ = 1.4%), whether or not there was a belly band. 2) Negative energy waves which depended on the density gradient, having $\underline{k}_{\perp}$ oriented the long way across the outer fan. On the worst field lines these modes required about 4% stream for stability in the hot electron anchor, but only 2% in the hot ion anchor; they did not occur at all with a belly band. Both ALC and negative energy waves were most unstable at frequencies between $2\omega_{ci}$ and $5\omega_{ci}$. Results will be presented on ray-tracing of waves across the field lines (radially and azimuthally) using a generalized ray-tracing method that is valid even when the group velocity is complex, and on the effect of radial mode structure on stability.

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# Electron Orbits in a Free Electron Laser with a Longitudinal Magnetic Wiggler*

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Analytic expressions for electron orbits in a longitudinal magnetic wiggler field of the form $\vec{B} = B_o[1 + \varepsilon \cos k_o Z]\vec{e}_z + \varepsilon B_o(k_o r/2) \sin k_o Z\vec{e}_r$ are derived by asymptotic techniques applicable to general wiggler configurations with strong guide fields. The implications of these orbits on FEL beam equilibria and amplifying gain problems will be discussed in detail.

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# TOWARDS A VECTORIZED MONTE-CARLO BEAM ORBIT CODE IN MHD EQUILIBRIUM GEOMETRY, WITH KITCHEN PHYSICS

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We are in the process of developing a vectorized beam orbit code for simulating neutral beam injection in time-varying, non-circular (but axisymmetric) tokamak magnetic fields. It is necessary in this code to preserve all the detailed "kitchen physics" already contained in the TRANSP beam orbit code, which now operates, as a scalar code, in concentric circular geometry. In addition to the physical processes included in the code at the time of Ref. 1, we now also take into account finite larmor radius effects, and full details of the beamlet divergeance geometry. In addition we perform a Monte-Carlo calculation of the beam ion distribution, as a function of minor and major radius, energy and pitch angle. This permits an accurate calculation of the beam-beam neutron production rate, and of the beam ion slowing down spectrum, as measured by scanning charge-exchange.

Advances towards a vectorized code in MHD equilibrium geometry include a fast method for inverting the MHD coordinate system to R,Y coordinates, and a scheme for vectorizing the complex branching logic of "kitchen physics" beam modeling. The inversion scheme involves a combination of cubic spline interpolation from a grid of pre-inverted points with an optimized Newton's method. The vectorization method we invision using involves the creation of a number of "lists" of particles waiting to 1. Orbit in magnetic coordinates, 2. Orbit in R,Y coordinates (near the magnetic axis), 3. Undergo Fokker-Planck collisions, 4. Undergo charge-exchange collisions, or 5. Travel as neutrals. At any moment the list with the largest number of members is tracked through a time-step, and the members of the list which remain after the timestep are distributed to the various lists, as appropriate. The central idea is to remove subroutine calls from inside the "innermost loops" and to ask subroutines to deal with a whole list of particles at a time rather than singly as it is currently done in our scalar code.

## REFERENCES

1. R.J.Goldston, D.C.McCune, H.H.Towner, et al., J.Comp.Phys., V43, p.61 (1981).

# A Model for Electron Currents Near a Field Null*

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The fluid approximation is invalid near a field null, since the local electron orbit size and the magnetic gradient scale length are comparable. To model electron currents in such a low-field region we propose a single equation of motion describing the bulk electron dynamics. The equation applies to the plasma within one thermal gyroexcursion of the field null. This region is treated as unmagnetized; electrons are accelerated by the inductive electric field and collisions with ions; damping is provided by electron viscousity. When combined with Faraday's law, this equation of motion indicates that electron viscousity may allow the field to reverse using neutral beam injection, provided the electron temperature remains low (<100eV). Application of this model to an FRM hybrid code (FROST)[1] will be presented.

References

1. R. Stark, G. H. Miley, "A 1-D Hybrid Code for FRM Start-up," Trans. Am. Nucl. Soc., 43, 390 (1982).

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# An Evaluation of Second Harmonic Electron Cyclotron Emission as an Electron Temperature Diagnostic for the TMX End Cell*

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The spectrum of second harmonic extraordinary mode electron cyclotron emission from the thermal plasma in the TMX end cell has been calculated for a variety of observation directions and plasma parameters. It will be shown that, except for a region near the center of the plasma, emission is not of sufficient intensity to reach the blackbody level, and therefore use of the spectrum as an electron temperature diagnostic is limited to this region. The calculated spectrum will be inverted to produce $T_e$, in order to demonstrate the regions where error occurs in using such a diagnostic, and the magnitude of the error.

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# TILTING STABILITY OF FINITE ASPECT RATIO ION RINGS.*

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Most results on the low frequency stability of field reversed particle ring plasma systems use analytic methods and are consequently valid only in the large aspect ratio limit, $R/\Delta R \gg 1$ and $R/\Delta Z \gg 1$ (R is the major radius and $\Delta R$, $\Delta Z$ are the radial and axial widths). We discuss a hybrid analytic-numerical method which allows stability results to be obtained for arbitrary aspect ratio rings. The method involves the numerical evaluation of the appropriate Vlasov time history integral ($\Delta L$ in the figure below), using orbits calculated numerically in actual, computationally determined equilibria. This method has been applied to the tilting stability of fat, elongated ion rings with $R/\Delta R \cong 1$ and $0.2 < R/\Delta Z < 0.7$. The figure shows sample results with the two frequencies $\Omega = \langle V_\theta / r \rangle$ and $\omega_z = 2\pi/T_z$ (bounce) determined numerically.

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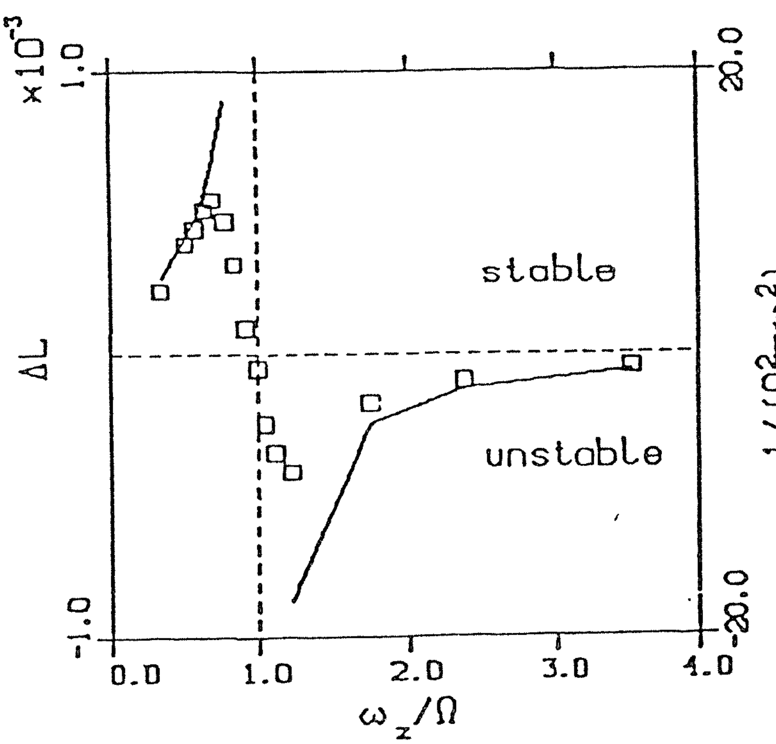
1.) See Phys. Fluids, 19, p723, (1976)



# PARTICLE MOTION IN THE FIELD OF A MODULATED WAVE*

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Particle motion in the field of a modulated wave, such as a standing wave, occurs in numerous fusion and other plasma physics applications. The particle's motion is governed by a Hamiltonian of the form

$$H = \frac{p^2}{2} - A(\varepsilon t) \cos[z - \phi(\varepsilon t)] \ .$$

In the limit $\varepsilon \rightarrow 0$, this system has an adiabatic invariant to all orders in $\varepsilon$. It is shown that this invariant can be recovered using Lie perturbation methods even though the Hamiltonian is nonseparable (not of the form $H_0 + \varepsilon H_1$, with $H_0$ integrable). It is also shown that in the limit $\varepsilon \rightarrow 0$, large-scale chaos still exists on a sufficiently long time-scale as a consequence of the original Hamiltonian's non-separability. The relation to applications is discussed.

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# LOWER HYBRID HEATING IN THE IGNITOR DEVICE*

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We examine numerically the effect of radio frequency (RF) heating at the lower hybrid (LH) frequency, in a compact high field toroidal plasma, Ignitor, including the effect of sawtooth oscillations. Significant heating can be achieved, as was also found in a previous study[1], which did not include the effect of sawtooth oscillations. At central temperatures of (3-5) keV the RF power deposition is found to be large over the entire inner half of the plasma minor radius, producing broad temperature profiles. The simulation model combines a one dimensional radial transport code (containing the effect of sawtooth oscillations)[2], and a toroidal ray tracing code (to calculate the energy deposition and power spectrum of the lower hybrid waves).[3] A quasilinear calculation of the electron distribution function is also done.

1. G. Cenacchi and A. Taroni, Proceedings of the Third Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas (Grenoble, 1982) Vol. III, 967.
2. L. Sugiyama and R. Englade, Massachusetts Institute of Technology M.I.T./R.L.E. Report PTP-82/14 (1982).
3. R. Englade, P.T. Bonoli and T. Antonsen, Proceedings of the Fourth Topical Conference on Radio Frequency Plasma Heating, (Austin, Texas 1981) Paper C14.

* Supported by USDOE

# Influence of Trapped Particles and Collisions on MHD Ballooning Modes*

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Estimates of beta limits in toroidal systems have continued to be based in large part on ideal MHD ballooning mode stability properties. It has been established in previous work that kinetic modifications can be important for these fine-scale (short-wavelength) modes.[1,2] For example, finite gyroradius effects associated with ion diamagnetic drifts can lead to significantly more optimistic beta criteria for specific tokamak equilibria of interest.[1] However, residual shear-Alfvén microinstabilities can be generated by magnetic drift resonances.[2] In the present work the kinetic analysis is generalized to include trapped-particle dynamics, the influence of collisions, and contributions from bounce and transit resonances. These stability calculations are interfaced with the familiar analytic model equilibrium[3] as well as with realistic numerical equilibria.[4] It is found that both the trapped-particle and collisional effects tend to reduce the growth rate of the ballooning modes. Reasons for this trend and its implications will be discussed. In order to produce a faster computational procedure for these studies, a reduced model including most of the important physics features has been developed. Results obtained from this code[2] are compared with those from the comprehensive but much slower general code.[4]

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

[1] W. M. Tang, R. L. Dewar, and J. Manickam, Nucl. Fusion 22, 1079 (1982).
[2] C. Z. Cheng, Nucl. Fusion 22, 773 (1982).
[3] J. W. Connor, R. J. Hastie, and J. B. Taylor, Phys. Rev. Lett. 40, 396 (1978).
[4] G. Rewoldt, W. M. Tang, and M. S. Chance, Phys. Fluids 25, 480 (1982).

# ELECTROMAGNETIC TURBULENCE AND DISSIPATIVE PRESSURE-DRIVEN MODES

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Recent investigation[1] has indicated that resistive ballooning instabilities may be significant impact on electron energy confinement in the ISX-B tokamak. The previous work utilized the reduced resistive MHD model. Here, we investigate the effect of electromagnetic turbulence on dissipative pressure-driven mdoes using a model which incorporates (linearly and nonlinearly) more complicated parallel electron dynamics.

Using a simplified set of moment equations, the renormalized electron fluid response is derived. In the parallel momentum balance equation (Ohm's Law), the physical effect of an electron pressure gradient measured along fluttering magnetic field lines leads to the presence of an anomalous electron viscosity and negative anomalous resistivity in the renormalized theory. The simultaneous presence of both these effects is necessary for conservation of energy. The combined effect of viscosity and resistivity is an energy transfer from short to long perpendicular wavelength, which results in strong nonlinear growth at long wavelength. This growth appears in the theory as a coupling of the usual ballooning instability to a (nonlinear) electromagnetic flute mode. Numerical studies of the eigenvalue problem will be present. Also, the renormalized electron temperature response is discussed.

Using the renormalized theory, an estimate of the level of magnetic turbulence necessary for hydrodynamic electron behavior is obtained. Preliminary results on the self-consistent determination of the saturated turbulence level and electron-thermal conductivity will be presented.

Reference

1. B. A. Carreras *et al.*, IAEA-CN-41/P-4.

# NOVEL METHOD FOR SOLVING STOCHASTIC EQUATIONS IN FREQUENCY SPACE*

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## ABSTRACT

In studies of homogeneous turbulence in fluids and plasmas, it is conventional to solve truncated k-space equations for the fields $\phi$ (or coupled sets for many fields) in the form

$$\frac{d\phi_k(t)}{dt} = -i\omega_{0k}\,\phi_k(t) + \gamma_k\phi_k(t) + \frac{1}{2}\sum_{k_1} V_{kk_1k_2}\phi_{k_1}(t)\,\phi_{k_2}(t) \quad ,$$

$(k_2 = k - k_1)$ by integrating in time into a stochastic stationary state. However, the real quantity of interest is not that $\phi_k(t)$, but the Fourier transform of the correlation function

$$\int d\tau\, e^{i\omega\tau} \int_{-T}^{T} \frac{dt}{2T}\,\phi_k{}^*(t)\,\phi_k(t+\tau) \quad \text{related to} \quad |\phi_{k,\omega}|^2 \quad .$$

We develop algorithms which solve exactly for $|\phi_{k,\omega}|$ from

$$\phi_{k,\omega} = \frac{1}{2}\sum_{k_1,\omega_1} \frac{V_{kk_1k_2}\,\phi_{k_1,\omega_1}\,\phi_{k_2,\omega_2}}{\varepsilon_{k,\omega}} \quad .$$

$(\omega_2 = \omega - \omega_1)$ where $\varepsilon_{k,\omega} = -i(\omega - \omega_{0k}) - \gamma_k$ is the linear dispersion function. Spectral methods can be used to evaluate the convolutions. The important advantage of the method is that it is easily generalized to problems with dispersion functions having complicated dependence on $\omega$ and many linear mode branches.

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3P17

# THERMAL INSTABILITIES IN THE EDGE REGION OF REVERSED-FIELD PINCHES*

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Due to high current and relatively low temperature, ohmic heating rates are fast enough to drive thermal instabilities in the edge region of Reversed-Field Pinches, on time scales of several tens of microseconds or less. For low beta an eigenvalue equation for cylindrical geometry is obtained. For the most interesting case of high mode numbers (hence small inductive effects) a cubic dispersion equation results, portending instability over a wide parameter range. In the physically interesting case when the parallel electron drift frequency is small compared with the ohmic heating rate, the radial extent of the unstable region around the field reversal layer is derived.

*Work performed under the auspices of the USDOE.

**On leave of absence from the Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

# Quasi-Statics of Two-Dimensional Plasmas

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## ABSTRACT

The generalized Ohm's law $E = \eta j - v \times B$ is studied coupled with the equilibrium condition; $0 = j \times B - \text{grad } p$. It turns out that the convection term $v \times B$ of the Ohm's law behaves as a nonlinear singular perturbation for the plasma current density during the quasi-static evolution in a two dimensional configuration. Roughly speaking, the diffusion coefficient parallel to magnetic surfaces we show must become infinite; this is required by the equilibrium condition which, in two dimensions, implies $j=j(\psi)$.

Bifurcation of the solutions is discussed. A linear eigenvalue problem is introduced to evaluate bifurcation points. It is shown that the solution of this nonlinear singular problem can evolve discontinuously if and only if the topology of flux contours changes. This pathological behavior is considered to have some connection to the major disruption observed in tokamaks.

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# STUDIES OF CURRENT GENERATION BY HIGH FREQUENCY WAVES IN TOROIDAL GEOMETRY*

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## ABSTRACT

We have incorporated recently developed theories of RF current generation[1] and RF power deposition[2] in a toroidal ray tracing code, and applied the theories to the study of current generation by waves in the electron cyclotron frequency range. The current drive theory includes the effects of anisotropic resistivity, electron acceleration by $\Delta B$, and RF induced trapping of circulating electrons. The RF power deposition profile in electron velocity space is calculated. The ray tracing code calculates self consistently the trajectory of wave packets and evolution of wave vectors in toroidal geometry. Parameters for study were chosen to correspond to the NRL-ORNL current drive experiment on ISXB. (However, the theory is relevant to other machines as well). It is found that the predicted level of current generated is sensitive to the angle of injection of the high frequency waves, as well as the value of the toroidal magnetic field. These findings should be useful in interpreting and optimizing experimental results.

*Supported by Department of Energy.

[1]T.M. Antonsen, Jr. and K.R. Chu, Phys. Fluids 25, 1295 (1982).
[2]K.R. Chu and B. Hui, Phys. Fluids (January 83).

# STABILIZATION OF THE TEARING MODE AT LOW DENSITIES BY TURBULENT ELECTRON DIFFUSION*

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Experimental results on Alcator C have indicated[1] that a threshold in plasma density must be surpassed before the tearing mode is observed. In contrast, resistive MHD theory predicts that if $\Delta'>0$, as is generally true experimentally, then instability occurs independent of density. In this work a kinetic approach to the tearing mode is developed which predicts stability for sufficiently large turbulent electron diffusion. Provided the electron diffusion coefficient scales inversely with density, ($D_e \sim 1/n$) implies that a density threshold exists. This theory utilizes the Normal Stochastic Approximation[2] to obtain the turbulent electron response, and the ion response is assumed to be classical. From this, a system of coupled, self-adjoint equations is obtained for the fluctuation potentials $\tilde{A}_\parallel$ and $\tilde{\phi}$. It is proved analytically that for $D_e$ above some value the energy drive of the tearing mode goes to zero, and hence the tearing mode is stabilized, whereas in resistive MHD theory one has $\Delta'>0$, which implies instability. Physically, electron diffusion prohibits the tearing region from becoming too small, whereas in resistive MHD the layer thickness is limited only by dissipation which alters the growth rate without affecting stability. Numerical solutions to the coupled self-adjoint system for $\tilde{A}_\parallel$ and $\tilde{\phi}$ are also presented.

*This work was supported by the U.S. Department of Energy under Contracts DE-AC02-78ET-51013 and W-7405-eng-26.

[1] R. Granetz, Phys. Rev. Lett. 49, 658 (1982).

[2] K. Molvig, J.P. Freidberg, R. Potok, S. Hirshman, J.C. Whitson and T. Tajima, in "Long Time Prediction in Dynamics", W. Horton, ed., J.C. Wiley (1982).

# A Phenomenological Theory of Nonlinear Saturation of Drift Wave Type Instability

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ABSTRACT

A phenomonologically motivated theory of nonlinear saturation of drift wave type instabilities is presented. While density gradient flattening is the physical saturation mechanism for collisional drift wave, that for trapped electron mode is found to be electron temperature gradient flattening. The importance of inclusion of radially nonlocal structure in the nonlinear analysis is demonstrated.

# BOUNCE-AVERAGED ICRH FOR TOROIDAL DEVICES*

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A nonlinear multispecies Fokker-Planck code with the capability to bounce average the differential operators which model Coulomb collisions, quasilinear resonant diffusion induced by weak wave-particle interactions, and an ohmic electric field has been used to evaluate the effects of ion cyclotron resonance heating in tokamaks. Salient properties of the RF wave field are determined using a one dimensional fluid model (e.g. relative polarization amplitudes). Warm plasma effects (finite $\kappa_{\perp}\rho$), nonlinear effects and effects dependent on the locally non-Maxwellian character of the distribution function are computed.

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# NUMERICAL CALCULATION OF AXISYMMETRIC COMPACT TORUS EQUILIBRIUM USING FINITE ELEMENTS*

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A method is presented for the calculation of an equilibrium in an axisymmetric compact torus. The plasma pressure is assumed to be a scalar quantity. The plasma and magnetic fields are determined by given adiabatic quantities, entropy, poloidal and toroidal magnetic flux. The calculation includes plasma outside the separatrix.

The calculation proceeds by alternating between the solution of the 2-D Grad-Shafranov equation and a 1-D flux surface average of this equation. The 2-D calculation utilizes flux surface coordinates and finite elements. The poloidal flux is obtained from the Grad-Shafranov equation which is solved on an approximate flux surface coordinate system using triangular finite elements. The points describing each surface are moved to coincide with surfaces of constant poloidal flux. The 1-D step computes the volume enclosed by each surface.

Three examples of equilibria are presented, two spheromaks and one field reversed configuration. Also an example of a transport calculation for a field reversed configuration is presented which uses this equilibrium calculation.

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Simulation of the Free Boundary Equilibria and Stability of Torus II Plasmas*

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We have investigated high beta free boundary equilibria consistent with Torus II magnetics using the recently developed Princeton Spectral Equilibrium Code (PSEC). Pressure profiles across the midplane are fitted to the results of multipoint Thomson scattering experiments, while external coil current distributions are related to Rogowski coil measurements by an inductance code. It is observed that PSEC converges only for a restricted range of safety factor profiles and plasma area. As the peak plasma pressure is increased, the code converges at larger $q_{edge}$ values and the plasma current decreases. Relatively narrow pressure profiles are required for a good fit to the experimental profile. The poloidal vertical magnetic field across the midplane is calculated and comparison is made with magnetic probe measurements. Vacuum flux contours are calculated both with and without the plasma. Separatricies are noted at both the top and bottom of the plasma. The stability properties of finite n ballooning fixed boundary modes and low n fixed and free boundary modes are compared with the instabilities observed experimentally.

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# CALCULATION OF THE LYAPUNOV SPECTRUM*

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## ABSTRACT

New techniques of nonlinear dynamics are starting to contribute to an understanding of some of the stochastic solutions of certain sets of nonlinear differential equations. One of the distinguishing features of these methods is that ensembles of realizations are chosen that have extremely closely bunched initial conditions. Linearizing around the central realization yields equations for the ensemble. Then the usual concept of statistical mixing over initial conditions is replaced by the concept of exponential separation of nearby orbits. The rate of exponentiation of this separation is called a Lyapunov number for the central realization. For an Nth order set of differential equations there are N such Lyapunov numbers, generally distinct. Frequently most of these are negative, corresponding to convergence of solutions. The distribution of the Lyapunov spectrum can be very helpful in understanding the dimensionality and complexity of a chaotic orbit.

Widely differing rates of exponentiation of solutions yields a difficult computational problem. Here a new approach is made for this problem. The matrix whose widely differing eigenvalues yield the Lyapunov spectrum is constrained to be diagonal for all time. The matrix of direction cosines relating the diagonal matrix to the given phase space is advanced in time by a well behaved set of equations. Examples will be given.

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

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# Ion Heating and Acceleration by Strong Magnetosonic Waves*

by

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ABSTRACT

A 1-2/2 dimensional fully electromagnetic, relativistic particle code is used to investigate the behavior of large amplitude magnetosonic waves propagating perpendicular to $\underline{B}$ for frequencies $\omega$ between the ion cyclotron frequency $\omega_{ci}$ and the lower hybrid frequency $\omega_{1h}$. When a low frequency external current $j_y = j_0 \sin(kx - \omega t)$ with $v_p (= \omega/k) \simeq v_A$ (where $v_A$ is the Alfven speed) is applied to a Maxwellian plasma including a magnetostatic field $B_{0z}$, magnetosonic waves with frequency $\omega$ are generated. As time progresses the amplitude of the longitudinal electric field $E_x$ builds up due to charge separation between ions and electrons which are of importance here. For large amplitudes, this field is found to accelerate some ions to the phase velocity of the wave (i.e., $v_A$) and trap them in the wave troughs; then, strong acceleration and heating of ions take place. This heating is associated with an acceleration of the trapped ions in the y direction parallel to the phase fronts due to the $\underline{v}_p \times \underline{B}/c$ force; it continues until the Lorentz force $\underline{v}_y \times \underline{B}/c$ is large enough to detrap the particles (i.e., until $\frac{v_y \times B_z}{c} \cong E_x$). The resultant velocity can be much higher than the Alfven velocity. The untrapped ions gyrate about the magnetostatic field.

These effects lead to heavy damping of the magnetosonic wave and to an extremely energetic ion tail on the ion distribution function with a maximum velocity of about 2.5 times $v_A$ in the present simulations. The parameters were: mass ratio $m_i/m_e = 50$, $\frac{eB_{0z}}{m_e \omega_{pe}^2 \lambda_D} = 10$, $\omega = 3.4\ \omega_{ci}$, $v_A/v_{te} = 1.414$, $T_i = T_e$.

Two additional characteristics have to be noted: first, these mechanisms are particularly interesting since waves of a broad range of frequencies will cause heating ($\omega_{ci} < \omega < \omega_{1h}$; no resonance is involved) provided that waves of sufficient intensity are produced. Second, the electrons are only poorly heated; however they play an important role through the strong charge separation effects and consequently cannot be neglected.

These results confirm quite well that magnetosonic waves are a good candidate for acceleration and heating of ions in a direction perpendicular to the magnetic field. They suggest an interesting mechanism for heating fusion plasmas.

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# A REAPPRAISAL OF NEOCLASSICAL ION HEAT CONDUCTION IN TOKAMAKS

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Conventional neoclassical theory starts with the statement that the lowest order particle distribution function $f_o$ must be Maxwellian because the terms in the drift-kinetic equation which tend to make f non-Maxwellian are higher order in $\rho_\theta/L$, where $\rho_\theta$ is the poloidal Larmor radius. In hot ion plasmas [$\rho_{i\theta T}/a > 0.2$, where $\rho_{i\theta T} = (2m_i T_{io}/e^2 B^2_{\theta a})^{1/2}$], $\rho_\theta/L$ is not a small parameter for the Maxwellian tail and there is experimental evidence that $f_o$ is non-Maxwellian away from the magnetic axis. In PDX the $\ell n$ f versus energy ($\varepsilon$) plot for a particular radius exhibits two straight lines with the higher energy part having an effective temperature $T_H = (\partial \ell n f_H/\partial \varepsilon)^{-1}$ approximately equal to the central (r = 0) ion temperature. A study of the D.K. equation with Fokker-Planck collision operator shows that, in the banana regime, the higher energy part of $f_i$ which is diffusing outwards in r and down in $\varepsilon$ will maintain an approximately constant effective temperature, but have a steep density gradient with $(\partial \ell n\ f_H/\partial r)^{-1} \sim \rho_{i\theta T}$. The lower energy part of $f_i$ which is diffusing inwards in r and up in $\varepsilon$ will have a lower temperature $T_c$ which varies with r. The discontinuity between the two parts of $f_i$ is a contact discontinuity in the phase space r, $|v|$ resembling the contact discontinuity known in gas dynamics. The non-Maxwellian tail has important implications for the ion energy content, the ion heat conduction, the energy transfer to electrons, charge exchange losses, etc., particularly in the outer regions of the discharge; all are increased substantially over the predictions using $T_c$. The Doppler-broadening temperature of impurity spectral lines will monitor $T_c$ and not $T_H$.

VARIATIONAL METHOD FOR THREE-DIMENSIONAL TOROIDAL EQUILIBRIA

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A variational method* has been proposed recently for computing three-dimensional toroidal equilbria with arbitrary pressure. The method obtains inverse solutions $R(v,\theta,\zeta)$, $\phi(v,\theta,\zeta)$ and $z(v,\theta,\zeta)$, where $(R,\phi,z)$ are cylindrical coordinates and $(v,\theta,\zeta)$ are "straight field line" coordinates. The inverse variables are Fourier-expanded in $\theta$ and $\zeta$, and a set of ordinary differential equations are derived for the amplitudes in $v$ from the variational principle. Natural boundary conditions, obtained from the variational principle for the parameterization of the outermost flux surface, provide one set of boundary conditions. The other set of boundary conditions is obtained by performing expansions near the magnetic axis. The equations for the Fourier amplitudes are solved numerically by collocation. The method is remarkably efficient. Results for toroidal stellarators, including those characterized by a spatial magnetic axis, will be presented.

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* A. Bhattacharjee, J. C. Wiley, and R. L. Dewar, Institute for Fusion Studies Report #48, University of Texas at Austin, Austin, Texas 78712, to be published in Phys. Fluids.

# Nonlinear Evolution of Tearing Modes

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## ABSTRACT

We present a formalism for treating the nonlinear tearing modes near the threshold with $\Delta'$ small, including both viscosity $\nu$ and resistivity $\eta$, $\eta \sim \nu \sim \varepsilon^3$. For the slab geometry, the amplitude A(t) of the linearly unstable mode evolves nonlinearly according to

$$\Delta' A = \mathring{A} F(a)$$

Where $a = A/\varepsilon^2$ and F(a) is defined by an integral of the stream function $\Phi$ satisfying

$$\partial^4 \Phi/\partial x^4 - [x \frac{\partial}{\partial\alpha} - a \sin\alpha \frac{\partial}{\partial x}]^2 \Phi = - x \sin\alpha$$

which is a linear equation for given a; x is the inner layer variable , $\alpha$ the helical variable my + nz. This shows that the nonlinear effects become important when $a \sim O(1)$ or $A \sim \varepsilon^2$ which is very small. For large a, $F(a) \sim \sqrt{a}$, in agreement with Rutherford's result. The mode does not saturate. Transition from linear to nonlinear phases is clearly shown.

For cylindrical geometry, the evolution equation becomes $[\Delta' + G(a)]A = \mathring{A} F(a)$, where F and G are defined by systems of linear equations for given a. The mode saturates if $\Delta' + G$ vanishes. Toroidal effects and nonlinear interaction of modes with different helicities lead to system of coupled evolution equations.

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# Computer Simulation of ECRH in an Inhomogeneous Magnetic Field

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## ABSTRACT

A relativistic electromagnetic particle code is used to simulate the absorption of extraordinary waves launched from the high field side. The plasam region contains the electron cyclotron and upper hybrid layers. At the cyclotron layer ($k_{\parallel} = 0$) the electric field vector of the extraordinary wave rotates in the direction opposite to the electron gyration. However, the electric field vector becomes elliptically polarized and rotates in the same direction as the electron gyration when the mode converted electron Bernstein wave reaches the electron cyclotron layer. This produces a strong electron cyclotron resonant heating until the relativistic effect detunes the wave. The relativistic effect also allows Bernstein waves to propagate beyond the cyclotron layer. Reemission of the extraordinary wave is observed when the electrons are in the decelerating phase of the wave. The localized electron heating gives rise to diamagnetic fields if the ions are allowed to follow the electrons to compensate the strong space charge field which would otherwise be generated.

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# Mode Conversion and Electron Heating near the Upper Hybrid Resonance Frequency*

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Mode conversion near the upper hybrid resonance frequency and the electron heating are studied using a one-dimensional electromagnetic particle code. It is found that the electron heating takes place more or less uniformly across a region between the upper hybrid resonance layer and the cyclotron layer where the frequency of the pump wave is equal to the electron gyrofrequency. In addtition, a significant fraction of electromagnetic energy associated in the pump is found to be reflected back to vacuum region at the upper hybrid resonance layer for both a strong ($E_o^2/8\pi nT_e = 0.94$) and a weak ($E_o^2/8\pi nT_e = 0.038$) pumps where $E_o$ is the electric field amplitude of the pump in vacuum.

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# MONTE CARLO STUDIES OF CENTRAL CELL ICRF HEATING AND RF START-UP IN TARA, AND RF FUELING IN MARS

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ABSTRACT

We are investigating central cell ICRF heating coupled with RF Start-Up in TARA, and RF Fueling of MARS, using a Monte Carlo simulation code. Compared to previous PHAEDRUS RF start-up studies, the former problem is highly collisional, while the latter is collisionless. We have, therefore, incorporated new techniques to improve the efficiency of the code in both limits. We will describe these improvements and present preliminary calculations for both TARA and MARS.

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# SAWTOOTH OSCILLATIONS, MAGNETIC DISTURBANCES, AND TOROIDAL FLUX REGENERATION IN THE ZT-40 REVERSED-FIELD PINCH*

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A comparison of experimental data with theoretical results indicates that the toroidal flux regeneration mechanism ("dynamo") in the Reversed-Field Pinch may be associated with the m = 1 tearing mode.[1] Discrete events are seen simultaneously on several diagnostics that are coincident with observable increases in the toroidal magnetic flux when the pinch parameter $\theta(\theta \equiv B_{\theta wall}/\langle B_z\rangle)$ exceeds 1.6.[2] The relative timing and the $\theta$ dependence of these events will be compared with the theoretical predictions.

Reference

1. E. J. Caramana, R. A. Nebel, D. D. Schnack, to be published in Phys. Fluids (May 1983).
2. R. G. Watt and R. A. Nebel, to be published in Phys. Fluids.

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# A THEORETICAL STUDY OF AXIAL CONFINEMENT IN TANDEM MIRRORS*

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The particle species in tandem mirrors are subjected to phenomena which can change the character of the distribution function near the loss boundary, thereby modifying axial confinement. For example, barrier warm and hot electrons are heated by ECRH, anchor hot $H^+$ ions in the MARS reactor are heated by ICRH, and passing central cell ions are subjected to strong radial transport due to drift pumping. Instead of using a bounce averaged Fokker-Planck code to determine axial confinement, we use analytic and numerical techniques applied to the high velocity expansion of the Fokker-Planck equation. This approximation: (1) is well justified for transport studies in the limits of large ambipolar potential and mirror ratio, (2) makes certain analytic calculations possible, and (3) considerably simplifies numerical codes. So far we have solved analytically the Pastukov problem in a spherical well including modifications due to strong radial transport, and find that axial confinement is improved between 20% and 30% by including radial transport, for a fixed confining potential. Numerical results pertaining to modifications from ECRH and ICRH heating, and further studies of the effect of radial transport will be presented.

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# BALLOONING MODES IN AXISYMMETRIC TANDEMS*

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The Lagrangian theory of finite-orbit corrections to MHD equilibrium and stability of collisionless systems in the paraxial limit is applied to finite-$\beta$ axisymmetric plasmas. The Lagrangian describes the incompressible motion of plasma and magnetic field lines in the paraxial limit. We derive Euler-Lagrange equations of motion that are second order in time, Fourier analyzed in angle, and fourth order in $\psi$ and z derivatives. Our numerical integration of the linearized Euler-Lagrange equations as an initial-value problem has been extended to the study of systems with finite curvature. We recover the correct growth rates for ideal-MHD interchange modes in the limit of no FLR effects. We have also calculated finite-$\beta$ paraxial equilibria for axisymmetric tandem mirrors with thermal barriers and hot electrons in preparation for numerical determination of ballooning-interchange growth rates and stability boundaries.

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# Necessary number of modes, multiplicity of asymptotic states, and hysteresis in Rayleigh-Bénard convection*

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A formula is derived for the number of Galerkin modes $N_{min}$ necessary to approximate the solutions of the 2D model of Rayleigh-Bénard convection. $N_{min} = 40$ for the parameter values which yield turbulent solutions of the 3-mode Lorenz system. N-mode approximations with $40 \leq N \leq 242$ yield states of steady convection as $t \to \infty$ for the initial conditions we have used.

Our numerical experiments have revealed the existence of many stable asymptotic states. Which of these is selected by the system depends on the initial velocity and temperature distributions and on the precise history of the temperature gradient across the layer. These numerical results are explained through an analysis of the bifurcations leading to new steady states as the Rayleigh number is increased.

The methods used are applicable to the study of MHD instabilities.

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# MODERATE-M BALLOONING MODES IN TANDEM MIRRORS*

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The β-limits on the center-cells of non-axisymmetric tandem mirrors due to moderate-m ballooning modes are studied. Both finite-Larmour-radius effects and corrections associated with the finite extent of the ballooning modes in the plane perpendicular to B are retained. The assumption of short perpendicular wavelength together with the large ellipticity of the flux surfaces near the MHD anchor cells allows one to reduce the three dimensional problem into a sequence of three one-dimensional problems as described in Ref. 1. We present marginal stability boundaries for two particular tandem mirror experiments. TMX-U[2] and MFTF-B[3]. The β-limits obtained from the moderate-m ballooning modes will be compared to the limits obtained from the low-m calculation of Ref. 4.

[1]W.M. Nevins and L.D. Pearlstein, Physics Basis for an Axicell Design for the End Plugs of MFTF-B, ed. by D.E. Baldwin and B.G. Logan, LLNL report UCID-19359 (1982), Appendix B.

[2]F.H. Coensgen et al., TMX-U Major Project Proposal, LLNL report LLL-PROP-172.

[3]K.I. Thomassen and V.N. Karpenko, An Axicell Design for the End Plugs of MFTF-B, LLNL report UCID-19318 (1982).

[4]T.B. Kaiser, W.M. Nevins, and L.D. Pearlstein, Phys. Fluids 26 (1983).

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# The Modelling of a Long, Thin Mirror Machine

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## ABSTRACT

In a very long, thin mirror machine the ion single particle dynamics are significantly altered from the usual conception of particles which are tied to field lines. Moreover, the electron and ion drifts are no longer equal in leading order. Thus, in addition to the implied modification of single particle motion, the macroscopic fluid, or guiding center plasma, models are also significantly affected. In order to study these effects we propose the following scaling to describe a long, thin mirror machine. We let R be the radius of the mirror machine, L its length, $\rho_i$, the ion larmor radius, $m_e/m_i \equiv \epsilon^2$ be the mass ratio of electrons to ions, and $V_e/V_i$ be the ratio of thermal velocities of ions to electrons. We assume $\rho_i/R = R/L = \epsilon$ and $m_i V_i^2 = m_e V_e^2$. Since we wish to study phenomena in drift time scales we assume that the characteristic times for fields to vary is $L/V_i$.

Within this scaling we find that there is no second adiabatic invariant for the ions and that in one pass through the machine an ion has an 0(1) shift in its field-line coordinate. In addition, both $\underset{\sim}{E}$ and $\langle \underset{\sim}{V} \rangle \times \underset{\sim}{B}$ are $O(\epsilon)$ (rather than 0(1) as is normal) so that it is not possible to determine B from $\frac{\partial \underset{\sim}{B}}{\partial t} = -\underset{\sim}{\nabla} \times \underset{\sim}{E} = \underset{\sim}{\nabla} \times \langle \underset{\sim}{V} \rangle \times \underset{\sim}{B}$. The electrons, on the other hand, possess both first and second adiabatic invariants, so that their distribution function is determined by a drift-kinetic equation for the motion averaged on a field line.

We construct a model with the ion motion determined by a guiding center plasma - like equations and the electrons determined by a bounce-averaged kinetic equation. The macroscopic momentum balance equations close the set for the particles. The electromagnetic fields are determined by Maxwell's equations and charge neutrality. This representation has certain elements of the well-known guiding center plasma model, the Darwin model, and the reduced equations model.

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Exact Nonlinear Solutions to the Reduced

MHD Equations and High Frequency MHD Activity

P. J. Morrison‡ and R. D. Hazeltine‡‡, Institute for Fusion Studies, The University of Texas at Austin, Austin TX 78712. We present a class of exact nonlinear stationary solutions to the reduced MHD (RMHD) equations. This class of solutions was obtained during an investigation of symmetries generated by the non-canonical Hamiltonian formulation[1,2] of RMHD. The low-$\beta$ RMHD equations are: $\dot{\psi} = [\psi,\phi] + [r^2/2, \phi]_p$ and $\nabla^2\dot{\phi} = [\psi,\nabla^2\psi] + [\nabla^2\phi,\phi] + [r^2/2,\nabla^2\psi]_p$. Here $[f,g] = r^{-1}[f_r g_\theta - f_\theta g_r]$, $[f,g]_p = r^{-1}[f_\zeta g_r - f_r g_\zeta]$, r and $\theta$ are poloidal polar coordinates, $\zeta$ is the azimuthal angle, and subscripts on the arbitrary functions f and g imply partial differentiation. The quantity $\psi$ is the poloidal flux; hence $\nabla^2\psi = J$, the toroidal current. The stream function is $\phi$ and $\nabla^2\phi = U$ is the vorticity. If we suppose $\psi$ and $\phi$ have the form $\psi(r, \theta-s(r)t, \zeta-t)$, then there exists a solution if $\psi = \phi + f(r)$. Here $s(r) = -c/2 - \beta/r^2$ is the poloidal speed and $f(r) = cr^2/4 + \beta \ln r + \gamma$, where c,$\beta$ and $\gamma$ are constants. This class of solutions includes localized structures that propagate (without plasma motion) in the toroidal direction at the poloidal Alfven speed, while moving in the poloidal direction at a speed determined by s(r). Such propagation implies high frequency ($\omega \gg \omega_*$) components in the spectrum of the poloidal flux, as are commonly observed in tokamak experiments.

1. P. J. Morrison, "Poisson Brackets for Fluids and Plasmas" in Math Methods in Hydrodynamics..., Eds. M. Tabor and Y. Treve, AIP Conference Proceedings #88, New York (1982).
2. R. D. Hazeltine and P. J. Morrison, Bull. Amer. Phys. Soc. 27, 1003 (1982).

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VARIATIONAL THEORY OF CURRENT DRIVE

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A variational theory for tokamak currents driven by waves is proposed. This theory is compared to earlier theories of current drive and offers important simplifications. In addition, the incorporation of toroidal effects into the theory will be discussed.

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# NUMERICAL STUDY OF THERMAL EQUILIBRIA AND THE CATASTROPHE MODEL FOR MAJOR DISRUPTION IN TOKAMAK*

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Thermal equilibria are studied by solving 1-D energy balance equations numerically. It is found that there exist three basic types of thermal equilibria corresponding to different boundary temperatures. The presence of fold catastrophe structure of curves of the temperature vs density indicates the existence of a density threshold for major disruption.

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# ANOMALOUS TRANSVERSE DIFFUSION OF ELECTRONS IN A UNIFORM MAGNETIC FIELD*

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## ABSTRACT

In a recent work,[1] this author has derived the transverse diffusion coefficient for a plasma in a magnetic field, applying a proposed approach to the definition of particle flux in terms of the statistical average of fluctuating displacements. We have proved that the resultant particle flux due to collisions with the same species vanishes to the first order in terms of the density gradient if the velocity distribution is Maxwellian. Our result also reduces to the form obtained by Longmire and Rosenbluth[2] with further assumptions. In this paper, we have evaluated the flux of test electrons due to collisions with background electrons and ions using our expression, and found anomalous super thermal test electron diffusion due to scattering by hot electron waves even in a local thermal equilibrium. Although the total electron flux due to collisions with electrons vanishes, the anomalous test electron flux can be large (positive or negative) depending on their speeds and pitch angles. This fact may explain anomalous energy loss by electrons for some extent.

[1]Kyoko Matsuda, General Atomic Report GA-A16836, 1982.

[2]C. L. Longmire and M. N. Rosenbluth, Phys. Rev. 103, 507, 1956.

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# Electron Cyclotron Radiation from Two Interpenetrating Plasmas in TMX-Upgrade

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Abstract

The emission and propagation of electron cyclotron radiation parallel to the magnetic field, arising from two different electron populations, are investigated. The electron populations are generated by ECRH, resulting in the thermal plasma (~1 kev) of the end cell and the hot electrons of the thermal barrier (~50 kev). The magnetic field and density profiles are those of TMX-Upgrade. Solving the full two component dispersion relation for the emission and absorption coefficients is difficult except for the case of thermal equilibrium. If the nonthermal component has a low density, an alternative approach can be used. In this case, hot electron collective effects are small, so that we can obtain the emission by integrating the single particle emissivity over the distribution function that is representative of the low density component, and obtain the absorption coefficient via Kirchhoff's law. We investigate the emission of the hot electrons , first using this single particle approach. We consider for the hot electrons the following distributions :relativistic maxwellian , relativistic maxwellian with a loss cone and a bimaxwellian. The warm electron emission is calculated separately via hot plasma theory and Kirchhoff's law. The effects of finite density of the hot electrons are then shown, using the maxwellian and bimaxwellian distribution functions for the hot electrons. Next we compare the results of the single particle approach with a solution of the full two component dispersion relation for the absorption coefficient. In this model the warm component is represented by a maxwellian and the hot component by a bimaxwellian . Since the distribution function is nonthermal, we cannot compute the emission directly from Kirchhoff's law. However, we estimate the emission, by solving, independently for each component, the single component dispersion relation for the absorption coefficient. We then use Kirchhoff's law to obtain the emission coefficient. The results of the two models for the absorption coefficient are compared to determine when the simpler, single particle approach can be used.

1) R.F.Ellis,Lasner,C.J.,Tsakiris,G.,Boyd,D.A.,Casper,T. Bull.Am.Phys.Soc. Vol. 27, No.8, Part B, p1137 (1982)

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# Mode Coupling Near Cyclotron Resonance in a Weakly Relativistic and Inhomogeneous Electron Plasma

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## ABSTRACT

It is known that the geometrical optics may breakdown near the second harmonic electron cyclotron resonance when the electron density is sufficiently high. In the so called dense regime, the two branches of the extraordinary mode (the electromagnetic and quasi electrostatic modes) are strongly coupled. In order to investigate the coupling between these modes, it is assumed that the external magnetic field is weakly inhomogeneous, so that $\underset{\sim}{B} = B_o(x)\,\underset{\sim}{\hat{z}}$, and a system of differential equations valid within the boundary layer $|x| < c/\omega$ is derived by reordering and solving the Vlasov equation. In the case of perpendicular propagation, these equations differ from those studied previously by Lazzaro, Ramponi, and Giruzzi (Phys. Fluids 25, 1220(1982).) The corresponding system for the fundamental resonance is also derived. Asymptotic behavior of the boundary layer solution is studied, in order to match these results to the waves outside the boundary layer. Energy balance relations are obtained using the appropriate Poynting theorems for the problem under consideration. Numerical results will be presented.

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# RF-Induced Spatial and Velocity-Space Diffusion in Cylindrically-Symmetric Mirrors*

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It is shown that the motion of high-energy (20-40 keV) ions in a symmetric mirror in the presence of a single resonant component of an electrostatic ion cyclotron mode is stochastic when allowance is made for the amplitude fluctuations typical of the 2XIIB experiment. The corresponding source-free Fokker-Planck equation is solved analytically. Due to the invariance of a generalized angular momentum, the radial diffusion of the plasma scales as $m^2$ times the velocity-space diffusion, where m is the azimuthal mode number (≃7). The radial diffusion time is roughly 0.3 ms for a typical high-energy ion.

In slab geometry the retention of the resonant term in the interaction Hamiltonian is roughly justifiable. This may not be the case in cylindrical geometry, especially for those particles with gyroradius comparable to their guiding-center radius. The appropriate equations of motion, retaining the effects of all the nonlinearly induced cyclotron harmonics of the gyromotion, are derived and examined.

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Spectrum of Dissipative Drift Wave

Turbulence in Tokamaks

P. W. Terry and P. H. Diamond, Institute for Fusion Studies, The University of Texas at Austin, Austin TX 78712. Recent investigations[1] have focused on the calculation of the spectrum of drift wave turbulence for the collisionless regime. Here, the spectrum of dissipative drift wave turbulence[2] is calculated using a model set of nonlinear fluid equations. In the course of this work, the effects of viscous, collisional dissipation on strongly correlated density fluctuations (clumps) are considered. Also, the toroidal Hasegawa-Mima equation[3] for ion dynamics is modified to include the stabilizing effect of parallel ion nonlinearity.

In considering the electron density fluctuation spectrum, a simplified set of nonlinear fluid equations is used to construct a two point correlation function equation. In addition to relative convection by $E \times B$ motion, the electron correlation equation contains a parallel collisional viscosity which is finite (in contrast to $E \times B$ term) at small separation. The effect of viscosity is to divide the electron density fluctuation spectrum into an "inertial range", where nonlinear mixing balances the source, and a "dissipation range", where viscous damping balances the source, thus destroying incoherent fluctuations. The electron correlation function is then used to obtain the collective resonance line width and growth enhancement.

Ion compton scattering and mode coupling are considered as saturation mechanisms. Preliminary results for electron heat transport in edge plasmas will be presented.

(1) P. H. Diamond, et. al, IAEA-CN-41/D-1-2 (1982).
(2) L. Chen, et. al, Nucl. Fusion 20, 901 (1980).
(3) E. A. Frieman and L. Chen, Phys. Fluids 25, 502 (1982).

# A NUMERICAL ANALYSIS OF THE EBT FLUTE MODES IN THE LOW POLOIDAL MODE NUMBER LIMIT*

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We have used an EBT radial stability code to investigate the stability of low and high frequency modes in the low poloidal mode number limit. The model ignores both poloidal and toroidal variations in the equilibrium parameters but treats the radial variation properly in the straight cylindrical limit. The model also assumes a bi-Maxwellian hot electron energy distribution along and perpendicular to the magnetic field lines, thus allowing for temperature anisotropy. We generally find an improvement in the stability over the slab model and the results seem to agree with the experiment. The stability boundaries will be presented.

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# A Resonant Cavity ICRF Coupler for Large Tokamaks*

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A new resonant cavity ICRF coupler is proposed for large tokamaks. The design features a novel resonant cavity, an rf magnetic field orientation that effectively radiates fast Alfvén waves, matching to 40 Ω transmission lines, and electric field orientation so that the strongest rf electric fields are orthogonal to the main toroidal magnetic field thereby benefitting from magnetic insulation. As a result, the power handling capability is excellent. For the case of the "Big-Dee" Doublet III tokamak, a single 35cm × 50cm coupler can launch 20 megawatts of fast Alfvén waves. Extrapolation to fusion reactor parameters is straightforward.

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# On the cut-off density of current drive by LH waves

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The current driven below the cut-off density by LH waves is very much higher than the theoretical value for an initially Maxwellian plasma without DC electric field. On the other hand, it can be shown that in the presence of a strong RF pump all of the electrons tend to run away if there is a DC electric field such that

$$N_{\parallel} n_{\boxed{13}} \lesssim 2(PV_L f^2 (1-\omega_{LH}^2/\omega^2)/R\ a(\Delta N_{\parallel}/N_{\parallel}))^{1/3}, \qquad (1)$$

where $n_{\boxed{13}}$ is the electron density in units of $10^{13}$ $cm^{-3}$, R and a are the major and minor plasma radii in m, f is the applied frequency in GHz, $V_L$ is the loop voltage, and P is the reactive power in MW. We find that under condition (1) the 2D QLFP equation has no adiabatic solutions such that $|\partial f^*/\partial t| << |\partial f^o/\partial t|$, where $f = f^o(t,u) + f^*$, $\int_{-1}^{1} d\ \xi\ f^* = 0$ and $\xi|\vec{v}| = v_{\parallel}$. This is in agreement with the fact that the RF-enhanced runaway production is a fast-time-scale process. The experiments show an order-of-magnitude decrease of $V_L$ during this transient regime. For the low asymptotic $V_L$ values a solution f* exists for a bi-Maxwellian-like $f^o(u)$ which yields the observed current level. The cut-off density is explained by the fact that under condition (1) there is substantial runaway production all over the plasma cross-section, whereas for higher densities the runaway production is relegated to the plasma periphery, leading to a presumably microscopically unstable configuration. On the basis of this criterion, which is in good agreement with the PLT, Alcator C, Versator II etc. density cut-offs, the prospects of LH current drive for reactor purposes look poor.

# Effects of the Hall Term on the Resistive Interchange Instability in Spheromak*

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Boundary layer analysis has shown that inclusion of the Hall effect into the resistive MHD model has a strong stabilizing influence on resistive instabilities in cylindrical geometry.[1] It is seen that the eigenfunctions become less localized and highly oscillatory in the presence of the Hall term so that connection of the resistive region solutions to the ideal region may be an important effect. In order to study this effect we have modified a linear initial value resistive MHD code and an asymptotic matching code to include the Hall term in Ohm's Law. This is easily accomplished in the initial value code by rewritting the magnetic field equation in the form

$$\frac{\partial}{\partial t}\left[\vec{B} + \frac{m_i}{e}\nabla \times \vec{v}\right] = \nabla \times \left[\vec{v} \times \vec{B} - \eta\nabla \times \vec{B}\right] .$$

Results from an application of these two codes to a study of the Hall term effects on the resistive interchange instability in Spheromak will be presented. Criteria are derived for the validity of the asymptotic matching approach and these are verified by comparison with the initial value code.

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

1 J. M. Finn and W. M. Manheimer, NRL Memorandum Report 4783.