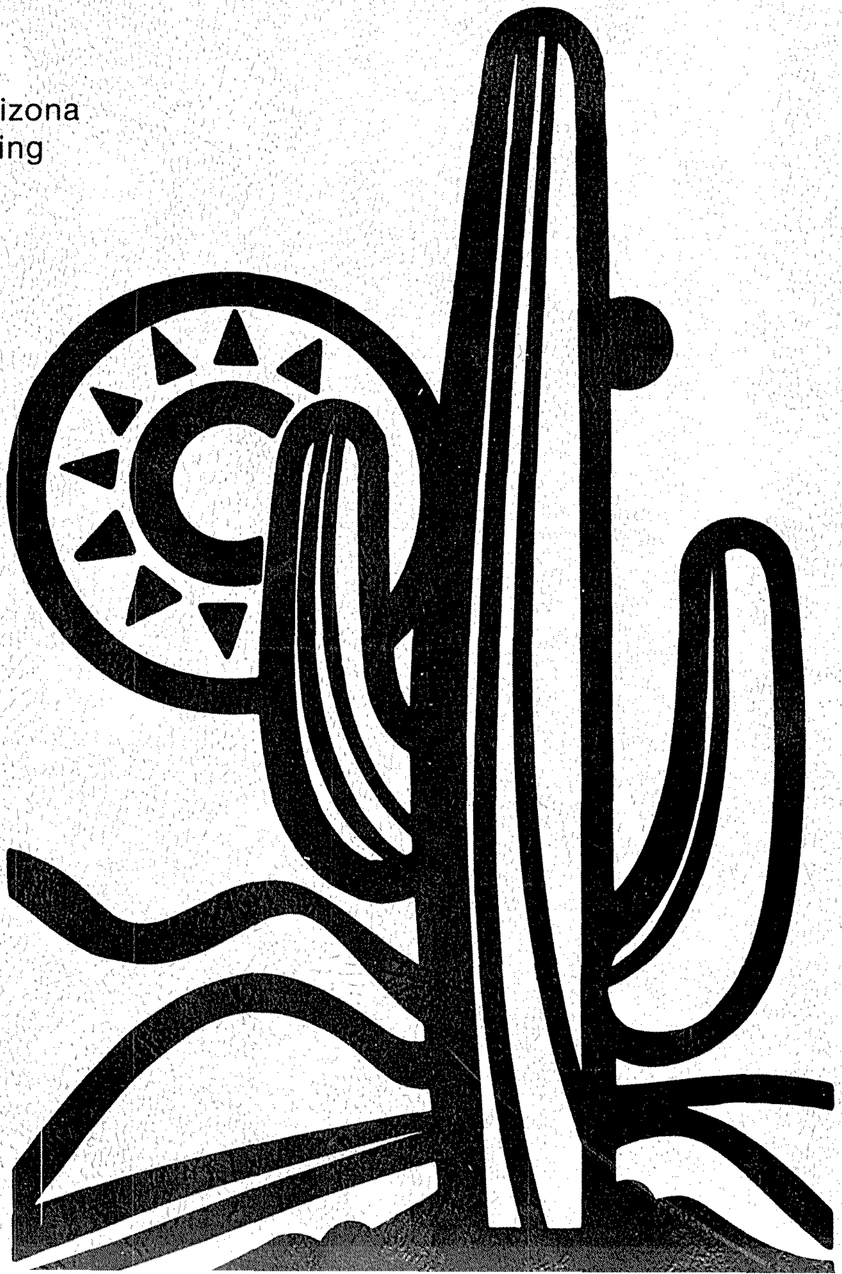
1980 SHERWOOD MEETING

THEORETICAL ASPECTS OF CONTROLLED THERMONUCLEAR RESEARCH

TUCSON, ARIZONA

APRIL 23-25, 1980

Sponsored by
The University of Arizona
College of Engineering
Tucson, Arizona



MINER

PROCEEDINGS OF THE SHERWOOD MEETING
THEORETICAL ASPECTS OF CONTROLLED THERMONUCLEAR RESEARCH

April 23 - 25, 1980

Marriott Hotel, Tucson, Arizona

Sponsored by

College of Engineering, The University of Arizona
Tucson, Arizona 85721

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General Information

All oral sessions will be held in the Little Theatre of the Tucson Community Center; all poster sessions will be held in the Grand Ballroom of the Marriott Hotel. Coffee and other refreshments will be available during the both the oral and poster sessions.

There will be two consecutive poster sessions on Wednesday afternoon and Thursday evening and one on Friday afternoon. Thursday afternoon is free.

A Cocktail Hour will be held in the Courtyard of the Marriott Hotel on Wednesday at 6:30 p.m. Two drinks are included in the registration fee.

The Registration and Travel desks are in the Lower Lobby of the Marriott Hotel. If you need assistance in planning transportation out, check with Travel early.

There were 251 papers submitted of which 21 were chosen for oral presentation. Provisions have been made for these authors to present the details of their work in a subsequent poster presentation.

SCHEDULE

Tuesday, p.m.

5:00 - 9:00	Registration and Cash Bar

Wednesday

8:15	Welcome
8:30	Oral Session 1A
10:30 - 10:45	Coffee
10:45	Oral Session 1A
12:15 - 1:15	Lunch
1:45 - 3:45	Poster Session 1B
3:45 - 4:45	Refreshments
4:15 - 6:15	Poster Session 1C
6:30	Cocktails

Thursday

8:30	Oral Session 2A
10:30 - 10:45	Coffee
10:45	Oral Session 2A
12:15 - 1:15	Lunch
	FREE AFTERNOON
7:00 - 9:00	Poster Session 2B
8:45 - 9:30	Refreshments
9:15 - 11:15	Poster Session 2C

Friday

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

1980 SHERWOOD MEETING
THEORETICAL ASPECTS OF CONTROLLED THERMONUCLEAR RESEARCH
April 23-25, 1980 -- Marriott Hotel -- Tucson, AZ

TUESDAY APRIL 22

5:00-9:00 REGISTRATION Exhibition Hall
CASH BAR Courtyard

WEDNESDAY APRIL 23

8:00-5:00 REGISTRATION
(Registration Desk open during all sessions)

8:15 WELCOME J. P. Schaefer
President of The University of Arizona
ANNOUNCEMENTS R. L. Morse

8:30 ORAL SESSION 1A

Little Theatre (Community Center)
R. D. Hazeltine and C. E. Seyler Chairmen

1A1. Generalization of Bohm Formula for Plasmas in MHD Regime. T. Ohkawa.
1A2. Resonant Diffusion in a Wave of Eikonal Form, and its Relation to the Chirikov Mapping. A. N. Kaufman, C. Grebogi, and H. D. I. Abqrbvanel.
1A3. A Theorem Concerning Induced Scattering in Plasma. S. Johnston.
1A4. Quasilinear Diffusion and Convection in a Torus. S. M. Mahajan, R. D. Hazeltine, and D. A. Hitchcock.

10:30-10:45 COFFEE BREAK

1A5. Stability of Drift and Trapped-Electron Modes in Tokamaks. L. Chen, C. Z. Cheng, and M. S. Chance.
1A6. Finite-n Ballooning-Mode Theory for High Beta Tokamaks. D. Dobrott and R. W. Moore.
1A7. n-Dependence of Ballooning Instabilities. R. L. Dewar, J. Manickam, R. C. Grimm, and M. S. Chance.

12:15-1:45 LUNCH

1:45-3:45 POSTER SESSION 1B

Optional Posters for Oral Papers 1A1-1A4

Grand Ballroom

1B1. Kinetic Theory of EBT Transport. M. Mond and Y.-P. Pao.
1B2. MHD Properties of Asymmetric Dees. F. J. Helton and N. Ohyabu.
1B3. The Tandem Tokamak. M. S. Chance, H. P. Furth, A. H. Glasser, and H. Selberg.
1B4. A Numerical Study of Rf-Heating in Deep Traps. D. Fyfe and I. Bernstein.
1B5. Kinetic Effects on the Ballooning Ion Temperature Gradient Drift Mode. P. W. Terry, W. C. Anderson, W. Horton, and C. Z. Cheng.
1B6. A Quasilinear Theory for Spatially Nonuniform Plasmas. C. E. Seyler.
1B7. Double Tearing Mode. J. K. Lee.
1B8. Thermal Equilibrium and Time Evolution of Thermal Instabilities. P. Rosenau and D. Degani.
1B9. Thermal and Radiation Losses in a Linear Device. D. Degani and P. Rosenau.
1B10. A Method for Obtaining Area-Preserving Discrete Equations (The Discrete Hamiltonian Method). C. R. Menyuk.
1B11. Wave Heating Models for Ion-Cyclotron Heating in EBT-S. J. L. Sperling, S. Hamasaki, H. H. Klein, and N. A. Krall.
1B12. A Model for Electron Ring Formation in EBT. S. Hamasaki, H. H. Klein, N. A. Krall, J. B. McBride, and J. L. Sperling.
1B13. Particle and Energy Confinement Time for Hill's Vortex. S. P. Auerbach and W. C. Condit.
1B14. Resonant Parametric Excitations at the Plasma Edge in Lower-Hybrid Heating of Tokamaks. E. Villalon.
1B15. Straight Line Orbit Stability Analysis of Mirror Confined Plasmas for Arbitrary Rho(i)/R(p). J. R. Myra, P. J. Catto, and R. E. Aamodt.
1B16. Anomalous Transport due to Shear-Alfven Eigenmodes. W. W. Lee, M. S. Chance, and H. Okuda.
1B17. Velocity-Space Dependences in Tandem Mirror Resonant Transport. R. H. Cohen.
1B18. Some Factors Influencing the Radial Structure of Tandem-Mirror Plasmas. M. E. Rensink and A. A. Mirin.
1B19. Effect of the High Energy Ion Tail on EBT Radial Transport. E. F. Jaeger and C. L. Hedrick.
1B20. Single Particle Drifts in Nearly Axisymmetric Magnetic Fields. H. Weitzner.
1B21. MHD Stabilization of Tokamaks by Helical Fields. J. P. Freidberg and P. A. Politzer.
1B22. Analysis of Properties of the MHD Particle Code. T. Tajima and F. Brunel.
1B23. Calculation of Ideal MHD Growth Rates in Field Reversed Mirrors for the Single Adiabatic and Double Adiabatic Models. D. V. Anderson, H. L. Berk, and J. H. Hammer.
1B24. Saturation of the Lower-Hybrid Drift Instability. Y.-J. Chen, C. K. Birdsall, and B. I. Cohen.
1B25. Macroscopic Stability of the Hot Electron Annulus in EBT. R. L. Miller.
1B26. Analytical Approximation of the Non-Adiabatic Particle Response. T. J. Schep and F. Pegoraro.
1B27. Parametric Studies of Instabilities Associated with Ring Distributions in Velocity Space. R. W. Huff, M. Ashour-Abdalla, J. N. Leboeuf, J. M. Dawson, and C. F. Kennel.
1B28. Fluctuations in Toroidal Geometry. D. A. Hitchcock, R. D. Hazeltine, and S. M. Mahajan.
1B29. Irreversibility and Transport in the Lower Hybrid Drift Instability. J. F. Drake.
1B30. Scaling of the Confinement Parameters in EBT. T. Uckan.
C 1B31. Parallel Electron Kinetic Effects and Electromagnetic Couplings for Mirror-Machine Microinstabilities. G. R. Smith and W. M. Nevins.
1B32. Effect of the Tearing Mode Growth Rate Due to the Presence of a Stochastic Magnetic Field. B. A. Carreras, M. N. Rosenbluth, and H. R. Hicks.
1B33. Fluid Turbulence Model of Disruptive Instability in Tokamaks. D. J. Tetreault.
B 1B34. Integral Equation Formulation of Collisionless Reconnecting Modes. B. Chike-Obi, G. Crew, T. M. Antonsen, Jr., and B. Coppi.
1B35. Scaling Characteristics of Hot Electron Rings in EBT. N. A. Uckan.
1B36. Energy Scaling of Runaway Transport by Magnetic Microturbulence: Comparison of Theory and Experiment. H. E. Mynick.
1B37. Effect of Plasma Diffusion on Mirnov Oscillations. D. Biskamp.
1B38. Summation of Oscillation-Center Expansions. E. Rosengaus and R. L. Dewar.
1B39. Guiding Center Orbits in MFTF-B Plug and A-Cell. J. A. Byers and L. D. Pearlstein.

1B40. MHD Stability of Equilibria with Flow. R. V. Lovelace.
1B41. Tearing Mode with Negative Delta Prime. X. S. Lee, S. M. Mahajan, R. D. Hazeltine, and D. W. Ross.
1B42. Implications of Recent Mathematical Results for Fluid Flow Simulation. Y. M. Treve.
1B43. Anomalous Transport and the "Principle of Profile Consistency". B. Coppi.
1B44. Stability of the field Reversed Mirror. E. C. Morse.
1B45. A Moments Approach for the Flux Surface Shift in Tokamaks. L. L. Lao, R. M. Wieland, W. A. Houlberg, and D. J. Sigmar.
1B46. Scaling of Energy Confinement Time: Error Estimates and Dependence on Plasma Temperature. D. Duchs, D. Pfirsch, and A. Schluter.
1B47. A Resistive Hybrid-Kinetic Model. J. P. Mondt.

3:45-4:45 REFRESHMENTS

4:15-6:15 POSTER SESSION 1C

Optional Posters for Oral Papers 1A5-1A7

Grand Ballroom

1C1. Electric Field Effects on Lower Hybrid Heating and Current Generation in Versator II. R. Englade, T. Antonsen, M. Porkolab, and N. Sharky.
1C2. A Theory of Modular Stellarators. J. A. Derr and J. L. Shohet.
1C3. Sloshing Ions in Tandem Mirror A-Cells. T. A. Cutler and M. E. Rensink.
1C4. Three Dimensional Equilibrium and Transport in EBT. W. H. Miner, N. K. Winsor, and H. Grad.
B 1C5. Geometric Optics in Plasmas Characterized by Non-Hermitian Dielectric Tensors. L. Friedland and I. B. Bernstein.
1C6. Toroidal Mode Structure of Lower Hybrid Waves. A. H. Glasser.
1C7. Magnetic Field Reconnection in Tokamaks Having Internal Magnetic Separatrices. M. Rosenberg and F. J. Helton.
1C8. Collisional Losses from Conventional and Tandem Mirror Traps. P. J. Catto and I. B. Bernstein.
1C9. On the Theory of Internal Disruptions in Tokamaks. N. One and D. Biskamp.
1C10. Evolution of a Long Compact Torus. R. N. Byrne and W. Grossmann.
1C11. Beta Limits for Torsatrons. F. Bauer, O. Betancourt, and P. Garabedian.
1C12. Stabilization of Residual Kink Modes in Doublets and Dee-Shaped Plasmas. L. C. Bernard, F. J. Helton, R. W. Moore, and R. L. Miller.
1C13. Tokamak Transport Calculations for Various Light and Heavy Impurities. R. A. Hulse and D. E. Post.
1C14. Theory of an Absolute Instability of a Finite-Length Free Electron Laser. P. C. Liewer, A. T. Lin, and J. M. Dawson.
1C15. Frequency Spectra and Parametric Dependences of EBT Core Plasma MHD Modes. D. A. Spong.
1C16. Effects of the Ohkawa, Bootstrap and Rotation Current on Co-Injection Beta-Limit Experiments. J. Hogan.
1C17. Endloss from a High-Beta Plasma Column. F. Brunel, T. Tajima, J. N. Leboeuf, and J. M. Dawson.
1C18. On the Possibility of Achieving Ignition in a High-Field Ohmically Heated Tokamak. C. E. Wagner.
1C19. Effect of Central Cell RF on Tandem Mirror Confinement. T. D. Rognlien and Y. Matsuda.
1C20. Stability of Doublets to Axisymmetric Resistive Modes. F. W. McClain.
1C21. Lower-Hybrid Wave-Driven Currents: MHD Constraints and Antenna Theory. D. A. Ehst and C. D. Boley.
1C22. Plasma Heating in a TRACT Reversed-Field Theta Pinch. L. Steinhauer.
B 1C23. Connection Rules for the General WKB Problem. W. M. Nevins, H. L. Berk, K. V. Roberts, and W. M. Sharp.

1C24. Helical Plasma Equilibria. M. S. Chu, C. Chu, F. W. McClain, M. Schaffer, and T. Ohkawa.
1C25. Simulation of the Formation Phase of Spheromak. Y. Li and D. D. Schnack.
1C26. Simulation of Low Frequency Doublet Heating. M. E. Kress and H. Grad.
1C27. Aspects of Drift Wave Turbulence in Tokamaks. P. H. Diamond and M. N. Rosenbluth.
1C28. Ballistic Propagation of Intense Ion Beams. W. B. Thompson.
1C29. Nonlinear Evolution of Ballooning Modes. W. Park, D. A. Monticello, R. B. White, H. R. Strauss, and S. C. Jardin.
1C30. Low Frequency Trapped-Electron Tearing Instability. R. Marchand.
1C31. Launching of Lower-Hybrid Waves in Self-Consistent Density Profiles. E. Valeo.
1C32. Effect of Finite Toroidal Mode Number on Ballooning Stability in Multipoles. E. A. Adler and Y. C. Lee.
1C33. The Integral Method in Linear Plasma Theory. G. Knorr.
1C34. Ballooning Mode Stability in Linear Multipoles. D. A. Skinner.
1C35. Penetration of Lower Hybrid Waves for Heating in Tandem Mirrors. K. A. Connor, J. T. Woo, D. B. Batchelor, and R. C. Goldfinger.
1C36. Single-Mode Saturation in Mirror Machines. R. C. Myer and A. Simon.
1C37. MTT--Modular Torus with Twisted Toroidal Field Coils. K. E. Weimer and J. L. Johnson.
1C38. Expanded Boundary Approach. N. Ohyabu.
1C39. Self-Similar Formulation of 1-D Plasma Flow. H. Hsuan and G. Elder.
1C40. Particle Simulations of Magnetic X-Points: Topology Change and Plasma Heating. J. N. Leboeuf, T. Tajima, J. M. Dawson, and E. Canobbio.
1C41. Calculation of Velocity Space Diffusion for a Chirikov-Taylor Model. A. B. Rechester and R. B. White.
1C42. Third-Order Electromagnetic Wave Interactions in a Plasma. W. B. Riesenfeld.
1C43. Startup of the Reversed-Field Pinch in a Quasi-Adiabatic Mode. E. J. Caramana.
1C44. Taylor Relaxation in a Torus of Arbitrary Cross-Section and Aspect Ratio. A. Reiman.
1C45. Ion Cyclotron Wave Propagation in a Hot Toroidal Plasma for R.F.Heating. M. Cotsaftis.
1C46. Microinstabilities in Tokamaks as an Initial Value Problem. C. Z. Cheng, C. O. Beasley, Jr., K. T. Tsang, D. J. Sigmar, and J. Denavit.
1C47. Time Evolution of Unstable Alpha Particle Distribution in Tokamak. D. J. Sigmar, W. I. Van Rij, and K. Molvig.

6:30 COCKTAILS Courtyard

THURSDAY APRIL 24

8:30 ORAL SESSION 2A

Little Theatre (Community Center)
T. D. Rognlien and R. L. Dewar Chairmen

2A1. Self-Consistent Potential Variations in Thermal Barriers. J. Kesner, G. Knorr, and D. R. Nicholson.
2A2. Fokker-Planck Studies of the Interaction Between Trapped and Untrapped Electrons in Magnetic Mirrors. A. A. Mirin, I. B. Bernstein, R. H. Cohen, and M. E. Rensink.

2A3. Electrostatic Drift-Ballooning Mode Turbulence in Tokamaks. S. P. Hirshman, P. H. Diamond, M. N. Rosenbluth, L. Chen, K. Molvig, J. C. Whitson, and J. Smith.

2A4. Variational Principle for Low Frequency Stability of Collisionless Plasmas. T. M. Antonsen, Jr., B. Lane, and J. J. Ramos.

10:30-10:45 COFFEE BREAK

2A5. Dynamical Determination of Ohmic States of a Cylindrical Pinch. D. D. Schnack.

2A6. Finite Beta Reversed-Field Pinches and Incomplete Relaxation. L. Turner and J. P. Christiansen.

2A7. Fast Alfven Wave ICRF Heating and Its Effect on Single Particle Confinement in Tokamaks Including Coulomb Collisions. K. W. Whang and G. J. Morales.

12:15-1:45 LUNCH

FREE AFTERNOON

5:00-7:00 NMFECC Users Group Meeting
Sinaloa Room

7:00-9:00 POSTER SESSION 2B

Optional Posters for Oral Papers 2A1-2A4

Grand Ballroom

2B1. Numerical Study of Low Toroidal Mode Number Instability in a Compact Torus. A. I. Shestakov, J. M. Sayer, and Y. Li.

2B2. Ion-Cyclotron Heating of a Vlasov-Fluid Theta-Pinch Plasma Column. R. Sanchez and F. L. Ribe.

2B3. Short Wavelength Collisionless Tearing Modes. R. G. Kleva.

2B4. Ohmic Heating Studies of the Reversed Field Pinch. R. Gerwin, R. W. Moses, Jr., and R. A. Nebel.

2B5. Numerical Modeling of Electron Diffusion Due to Disturbed Flux Surfaces. M. G. McCoy, A. A. Mirin, and R. W. Harvey.

2B6. Plasma Edge Boundary Conditions for 3D Plasma Transport. H. Grad.

2B7. Enhanced Single-Particle Confinement in the Elmo Bumpy Torus Concept. R. A. Dandl, D. Dobrott, G. Guest, and W. Bard.

2B8. Stable Startup and Burn Simulations for a Reversed Field Pinch. R. A. Nebel, G. H. Miley, and R. W. Moses.

2B9. Plasma Potential Modification and Cold Ion Stoppering Due to Ponderomotive Effects on Electrons. R. A. Jong, W. J. Fader, and E. A. Sziklas.

2B10. Model of a Plasma Hitting Neutral Gas. A. H. Boozer and R. A. Jacobsen.

2B11. Magnetic Flux Diffusion in a Tokamak Reactor. Y.-K. M. Peng, J. A. Holmes, and K. E. Rothe.

2B12. Relaxation of Neutral Beams in the Presence of High Frequency Instabilities. D. K. Bhadra, S. C. Chiu, and R. W. Harvey.

2B13. Heating by Collisional Slowing of Fast Ions in Non-Circular Tokamaks. L. M. Hively, J. Rome, and G. H. Miley.

2B14. Variational Theory of Electrical Conductivity and Kinetic Tearing Modes. C. S. Chang, R. R. Dominguez, and R. D. Hazeltine.

2B15. Two-Dimensional Simulation of the Formation of the PPPL Spheromak. H. C. Lui, C. K. Chu, and A. Aydemir.

2B16. Influence of Cross-Field Diffusion on the Stability of the Collisional Drift Wave. C. L. Chang, J. F. Drake, A. B. Hassam, and C. S. Liu.

2B17. Simulations of the Formation and Evolution of the PS-1 Spheromak. A. G. Sgro, D. Winske, C. K. Chu, and H. C. Lui.

2B18. Extended Time Behavior of an Unstable or Damped Single Mode. T. Dewandre and A. Simon.

2B19. Nonlinear Evolution of Rippling Modes in Cylindrical Geometry. H. R. Hicks, P. W. Gaffney, B. Carreras, D. K. Lee, and V. E. Lynch.

2B20. Interchange Stability of Plasma Confined by Field-Reversed Ion Rings. A. Mankofsky, L. Sparks, R. N. Sudan, and J. Denavit.

2B21. Rippling Modes in the Edge of a Tokamak Plasma?. J. D. Callen and M. E. Benchikh-Lehocine.

2B22. Ion Cyclotron Resonance Heating in a Tandem Mirror. J. E. Howard and J. Kesner.

2B23. Monte Carlo Simulation of Helium Ash Enrichment in a Proposed ETF/INTOR Divertor. D. Heifetz, D. E. Post, and M. Petravic.

2B24. Tearing Mode Stability of a Long-Thin Reversed-field Theta Pinch. J. M. Sayer, D. D. Schnack, and H. L. Berk.

2B25. 2-D Numerical Calculations of Field Reversed Plasmas. R. D. Milroy and J. U. Brackbill.

2B26. Application of a Unified Theory to the Charged-Particle Slowing-Down in Superdense Fusion Plasmas. M.-Y. Hsiao and C. K. Choi.

2B27. Neo-Classical Transport Coefficients in the Plateau Regime for Arbitrary Cross Section and Beta. H. K. Meier and D. J. Sigmar.

2B28. Functional Integral Approach to Classical Statistical Dynamics. R. V. Jensen and C. Oberman.

2B29. Diffusion and Magnetic Energy Dissipation in Field Reversed Plasmas. J. D. Huba, J. F. Drake, and N. T. Gladd.

2B30. Analytic Mirror Equilibrium Studies. D. A. D'Ippolito and J. P. Freidberg.

2B31. Numerical Simulations on Poloidal Divertors. T. Takizuka, H. Okuda, and W. W. Lee.

2B32. Anomalous Ion Thermal Conductivity from Drift Waves. W. Horton and D. Biskamp.

2B33. Reconnection, Compression and Tilting of a Reversed Slab Theta-Pinch with Endloss. F. Brunel, T. Tajima, and J. M. Dawson.

2B34. The Velocity Distribution of Alpha Particles and Collisional Heating in Thermonuclear Plasmas. J. D. Gaffey, Jr. and R. S. Schneider.

2B35. Simulation of Heating Efficiency by Lower Hybrid Waves. V. K. Decyk, J. M. Dawson, and G. J. Morales.

2B36. Noncanonical Hamiltonian Density Formulation of Hydrodynamics and Ideal MHD. P. J. Morrison and J. M. Greene.

2B37. Mechanism for Energetic Ion Losses in Tokamaks. F. L. Hinton.

2B38. Energy Principle with Global Invariants. A. Bhattacharjee, R. L. Dewar, and D. A. Monticello.

2B39. Diffuse Boundary Equilibria for the BYU Topolotron Experiment. S. N. Rasband and D. Peterson.

2B40. Kinetic Effects on Ballooning Modes. J. W. Connor, R. J. Hastie, and W. M. Tang.

2B41. Power Absorption of Lower Hybrid Waves near Mode Conversion in the Presence of Ion Cyclotron Harmonics. K. Ko, V. Fuchs, and A. Bers.

2B42. Nonlinear Evolution of Tearing Instabilities: Coalescence of Magnetic Islands. C. C. Wu.

2B43. Nonlinear Theory of High-m Tearing Modes. R. R. Dominguez, M. Rosenberg, and C. S. Chang.

2B44. Ideal and Resistive MHD Stability Computations for a Finite-Length Cylindrical Spheromak. G. J. Marklin, C. S. Liu, and J. M. Finn.

2B45. Nonlinear Saturation of Current Driven Drift Waves. A. K. Sen, T. Tange, and K. Nishikawa.

2B46. Free Electron Laser with a Strong Electric Field. Y. P. Ho, Y. C. Lee, and M. N. Rosenbluth.

2B47. Rotation Model for Field-Reversed Theta Pinch. Q. T. Fang and G. H. Miley.

8:45 9:30 REFRESHMENTS

9:15-11:15 POSTER SESSION 2C

Optional Posters for Oral Papers 2A5-2A7

Grand Ballroom

2C1. Dimensionality and Lyapunov Numbers of Strange Attractors. E. Ott, J. Hanson, and D. A. Russell.
2C2. Drift Modes in the Central Cell of Tandem Mirrors. W. Horton.
2C3. Alpha Particle Driven Compressional Aflven Wave Instability in a Tandem Mirror Reactor. J. D. Hanson and E. Ott.
2C4. Tearing-Mode Stability Properties of a Field-Reversed Ion Layer at Marginal Stability. J. Chen and R. C. Davidson.
2C5. Temporal Evolution of Nonlinear Lower-Hybrid Waves. C. F. F. Karney.
2C6. Adiabatic Theory for a Single Nonlinear Wave in a Vlasov Plasma and an Explanation of Electron Holes. V. B. Krapchev and A. K. Ram.
2C7. Conflicting Current Profile Requirements for Ideal MHD Stability and Resistive Diffusion Control in a Tokamak. L. A. Charlton, D. B. Nelson, R. A. Dory, and D. K. Lee.
2C8. Studies of Local Magnetic Ripple Effects in Tokamaks. R. H. Fowler, J. A. Rome, V. E. Lynch, and J. F. Lyon.
2C9. Monte Carlo Evaluation of Transport in Stellarators and Tokamaks with Ripple. G. Kuo-Petravic and A. H. Boozer.
2C10. Variational Formulation and Adiabatic Compression of Rotating Plasmas. D. Stevens, E. Hameiri, and W. Grossmann.
2C11. Plasma Heating by Magnetosonic Waves in High Beta Plasma. K. Nozaki, B. D. Fried, and G. J. Morales.
2C12. Electron Landau Damping of Loss-Cone Instabilities in a Mirror Reactor Regime. M. J. Gerver.
2C13. Analytic Reversed-Field MHD Equilibria as "Most Probable States". G. Vahala, J. Ambrosiano, and D. Montgomery.
2C14. Most Probable MHD Equilibria for Tokamaks and Reversed Field Pinches. J. Ambrosiano and G. Vahala.
2C15. Simulation of Impurity Injection Into ISX-B. E. C. Crume, Jr., D. E. Arnurius, and R. C. Isler.
2C16. Adiabatic Compression and Neutral Beam Buildup in a Field Reversed Mirror Configuration. J. K. Boyd, S. P. Auerbach, H. L. Berk, B. McNamara, and P. A. Willmann.
2C17. Field-Reversed Mirror Transport Code. d. E. Shumaker, J. K. Boyd, S. P. Auerbach, H. L. Berk, and B. McNamara.
2C18. Magnetic Field Profiles from Inverse Normal Mode Problems. T. E. Cayton and D. C. Barnes.
2C19. Statistical Mechanics for the Model System of the Forward Raman Instability. G. Schmidt, T. Tajima, and R. Pellat.
2C20. Magnetic Field Curvature in Torsatrons/Stellarators. D. T. Anderson and J. L. Shohet.
2C21. Linear Theory of the Ordinary Mode Electron Cyclotron Resonance Heating in Tokamak Plasmas. V. Arunasalam, P. C. Efthimion, J. C. Hosea, and H. Hsuan.
2C22. Rotation of a Field Reversed Theta Pinch. D. C. Barnes and C. E. Seyler.
2C23. Absorption of Wave Momentum by Trapped Electrons. N. J. Fisch.
2C24. Integral Method for Solving Tokamak Equilibria. T. Mizuguchi, T. Kammash, D. J. Sigmar, and H. K. Meir.
2C25. Interpretation of the Collisionless Drift Mode in a Sheared Magnetic Field. C. Grebogi and R. M. Kulsrud.

2C26. Beta Optimization of Non-Circular Tokamak Equilibria to Ideal MHD Modes. R. W. Moore, L. C. Bernard, F. J. Helton, and R. L. Miller.
2C27. Nonlinear Propagation and Coupling of Lower Hybrid Waves Excited by a Waveguide Array. K. Theilhaber, K. Ko, V. Krapchev, and A. Bers.
2C28. Self-Consistent Vlasov Description of the Free Electron Laser Instability in a Relativistic Electron Beam with Uniform Density. R. C. Davidson and H. S. Uhm.
2C29. Feasibility and Credibility of a Three-Dimensional Relativistic Electromagnetic Particle Code Based on a 2*128**3 Grid. O. Buneman.
2C30. AC Conductivity in a Homogeneous Plasma from a Convergent Collision Integral. R. L. Guernsey and J. P. Mondt.
2C31. The Effect of Scattering by Density Fluctuations on the Accessibility of Lower Hybrid Waves. P. T. Bonoli and E. Ott.
2C32. Toroidal Rotation Effects in Beam-Heated Tokamaks. W. A. Cooper and J. T. Hogan.
2C33. The Second Region of Stability. J. M. Greene and M. S. Chance.
2C34. On the MHD Continuous Spectrum in General Toroidal Geometry. J. A. Tataronis.
2C35. Effects of Fast-Wave Heating on EBT Ion Transport. R. B. Campbell, R. J. Kashuba, and T. Kammash.
2C36. SKELETOMAK - High Beta Tokamak with a MHD "Rigid" Spinal Column. P. Kaw, W. Park, and E. Valeo.
2C37. Spectral Estimates, Stability Conditions and the Rotating Screw Pinch. E. Hameiri.
2C38. Diffusion of Charged Fusion Reaction Products by Transient Magnetic Fluctuations. F. Pegoraro and B. Coppi.
2C39. The Problimak: A Non-Tilting Field-Reversed Equilibrium. J. H. Hammer.
2C40. Stochastic Properties of the Chirikov-Taylor Mapping. H. D. I. Abarbanel, C. Grebogi, and A. N. Kaufman.
2C41. Chaotic (Strange) and Periodic Behavior in Instability Saturation by the Oscillating Two-Stream Instability. D. Russell, E. Ott, and J.-M. Wersinger.
2C42. On the Plasma Dispersion Relation Near the Two-Ion Hybrid Resonance. S. C. Chiu, V. S. Chan, and J. Y. Hsu.
2C43. Classical Transverse Transport Processes in a Strong Magnetic Field. Y. P. Ho.
2C44. On the Mercier Criterion in Guiding Centre Theory. A. Salat.
2C45. Long Time Equilibrium in a Cylinder. P. N. Hu.

FRIDAY APRIL 25

8:30 ORAL SESSION 3A

Little Theatre (Community Center)
D. B. Batchelor and S. Johnston Chairmen

3A1. Steady State Field-Reversed Equilibria with Applied Quadrupole Fields. H. L. Berk and J. H. Hammer.
3A2. Numerical Simulation of m = 0 Phenomena in Field Reversed Configurations Using a Two and One-Half Dimensional Hybrid Code. D. W. Hewett.
3A3. The Physics Basis for EBT-P. C. L. Hedrick.
3A4. Non-Local Stability Analysis of EBT Plasma. J. W. Van Dam, Y. C. Lee, and M. N. Rosenbluth.

10:30-10:45 COFFEE BREAK

3A5. Theory of Spheromak Equilibrium and Stability - Minimum Energy State for a Finite Cylindrical Plasma. Z. G. An, A. Bondeson, H. H. Chen, Y. C. Lee, C. S. Liu, G. Marklin, E. Ott, J. Finn, and W. Manheimer.
3A6. Two-Dimensional Modeling of the Formation of Spheromak Configurations. S. C. Jardin, W. Park, and M. Okabayashi.
3A7. MHD Optimal Stellarator Field. W. Dommaschk, J. Nuhrenberg, and A. Schluter.

12:15-1:45 LUNCH

1:45-3:45 POSTER SESSION 3B

Optional Posters for Oral Papers 3A1-3A7

Grand Ballroom

3B1. Enhanced Fusion Product Heating via Compressional Alfven Instability. W. R. Sutton and G. H. Miley.
3B2. FRM and Ion Ring Equilibria for the Ringhybrid Code. A. Friedman.
3B3. Simulation of Rotation in Linear Magnetic Systems. F. L. Cochran, R. Morse, and G. Sowers.
3B4. Force-Free Magnetic Fields in Non-Circular Cylinders. C. Chu and M.-S. Chu.
3B5. Calculations of Neutral Beam Power Deposition for Doublett III. R. W. Harvey, D. K. Bhadra, and S. C. Chiu.
3B6. Similarity Solutions for Decay and Rotation Generation in a Reversed Field Theta Pinch. J. M. Finn and W. Manheimer.
3B7. ZT-40 Startup Models. R. N. Byrne and C. K. Chu.
3B8. Kinetic Modeling of Hot Electron Rings. D. C. Baxter.
3B9. Interchange Mode Growth Rates Around the Magnetic Axis. J. J. Ramos and T. M. Antonsen.
3B10. Effects of q(psi) on the Ballooning Mode Second Stability Region. L. Sugiyama and J. W.-K. Mark.
3B11. MHD Stable Confinement Configurations in High-Beta Regimes. A. Ferreira, B. Coppi, and J. J. Ramos.
3B12. Stabilization of the m=2 Tearing Mode by the Electron Temperature Gradient. N. T. Gladd, J. F. Drake, Y. C. Lee, and C. S. Liu.
3B13. The Case for the Electron Energy Loss in Tokamaks Being Mainly an Energy Transfer to the Ions. A. A. Ware.
3B14. Strong Turbulence, Waves, and the Failure of Weak Turbulence Theory. H. A. Rose and D. F. Dubois.
3B15. Equilibrium and Adiabatic Compression of a Free Boundary Doublet. S.-L. Wen and H. Grad.
3B16. Effects of the Fast Wave on the Drift-Cyclotron Loss-Cone Mode. K.-C. Shaing.
3B17. Ballooning Formalism Calculation of Electromagnetic Trapped-Particle Modes. G. Rewoldt, W. M. Tang, and E. A. Frieman.
3B18. Scattering of Lower-Hybrid Waves by Density Fluctuations. P. L. Andrews and F. W. Perkins.
3B19. Resonant Absorption of Alfven Waves. P. L. Pritchett and E. Canobbio.
3B20. The Dispersion Functional for a Two-Component Vlasov Plasma and for the Vlasov-Fluid Model. K. R. Symon, C. E. Seyler, and H. R. Lewis.
3B21. Finite Larmor Radius Stabilization of Ballooning Modes. K. T. Tsang and J. Whitson.
3B22. Third Order Reduced Equations for Tokamaks. H. Strauss.
3B23. Energy Confinement and Transport in Torsatrons. R. E. Potok, P. A. Politzer, and L. M. Lidsky.
3B24. Electron Cyclotron Radiation Emission from a Mirror Plasma. C. M. Celata.
3B25. Coherent Wave-Particle Effects in EBT Annulus Formation. D. B. Batchelor and R. C. Goldfinger.

3B26. Drift Waves in Cylindrically Symmetric Systems with Strong Magnetic Shear. R. Linsker.
3B27. Model for Particle Transport in Tokamaks. N. Sharky and B. Coppi.
3B28. The Resonance Absorption of Axially Asymmetric Alternating Fields in a Inhomogeneous Plasma. V. I. Laphsin, J. L. Shohet, K. N. Stepanov, and A. M. Gorkii.
3B29. Resonant Absorption of Alfven Waves. P. L. Pritchett and E. Canobbio.
3B30. Ballooning Modes in Multiple Mirrors. T. B. Kaiser and G. Vandegrift.
3B31. Resistive Tearing Modes in the Field Reversed Theta Pinch. T. G. Hewitt.
3B32. Dispersion Differential Equation for a Straight Vlasov-Fluid Screw Pinch with Small Ion Gyroradius. H. R. Lewis.
3B33. PEST2--Ideal MHD Stability in General Toroidal Coordinates. R. C. Grimm, R. L. Dewar, and J. Manickam.
3B34. Bremsstrahlung Spectra Associated with Anomalous Electron Thermal Conduction. J. C. Wiley and F. L. Hinton.
3B35. Whistler Instability in EBT. P. N. Guzdar and R. Marchand.
3B36. Tokamak Plasma Heating with Intense Pulsed Ion Beams. W. M. Manheimer and N. K. Winsor.
3B37. Stability Boundaries for Large Scale, High Beta Mirror Machines. K. Molvig and L. D. Pearlstein.
3B38. Theoretical Analysis of Ion Cyclotron Fluctuations in Tokamaks. R. E. Waltz and R. R. Dominguez.
3B39. A Diffusing Test Particle Superposition Principle for Electrostatic Drift Wave Turbulence. K. Swartz and K. Molvig.
3B40. Resistive MHD Calculations in Moderate Beta Tokamaks. J. A. Holmes, B. Carreras, W. A. Cooper, H. R. Hicks, and V. E. Lynch.
3B41. Relativistic Effects on Strong Langmuir Turbulence. H. P. Freund, C. S. Liu, and R. M. Kulsrud.
3B42. The Effect of Low Frequency Density Fluctuations on Electron Cyclotron Resonance Heating. B. H. Hui, P. N. Guzdar, and E. Ott.
3B43. Improvement of Tokamak Plasma Heat Containment by Poloidally Asymmetric Heating. S. K. Wong and K. H. Burrell.
3B44. Finite Larmor Radius Modifications of an MHD Instability. J. L. Schwarzmeier.

1A1

ORAL SESSION

GENERALIZATION OF BOHM FORMULA FOR PLASMAS IN MHD REGIME

TIHIRO OHKAWA

General Atomic Company
San Diego, California 92138

Many experiments have shown that the transport rate of turbulent plasmas is described by the Bohm rate.$^{(1)}$ Experimental parameters were such that the plasmas were in electrostatic regime, i.e., the beta value β (the ratio of the plasma pressure to the magnetic pressure) is much smaller than the ratio of electron mass m_e and ion mass m_i, $\beta << m_e/m_i$. Recent experiments with tokamaks have shown that the transport rate is governed by a different type of scaling.$^{(2)}$ The plasmas are magnetically turbulent and are in the regime $\beta > m_e/m_i$, where electrostatic fluctuations couple significantly to electromagnetic fields. The purpose of this work is to derive the transport rate for turbulent plasmas in this mhd regime in analogy to the Bohm rate for turbulent plasmas in the electrostatic regime. Heuristic arguments will be used in the calculation in the same spirit as the derivation of Bohm's formula.

We consider turbulent plasmas in mhd regime. The turbulence has perpendicular and parallel components of electric field, $E_\perp$ and $E_{||}$ related by Alfven wave dielectrics.

$$\frac{E_{||}}{k_{||}} = \frac{E_\perp}{k_\perp}\left(1 - \frac{\omega^2}{k_{||}^2\ v^2}\right) \tag{1}$$

where $k_\perp$ is the perpendicular wave number and v_A is the Alfven speed.

The parallel response of electron density to the fields is given by

$$n_1 = \frac{en_o}{T_e}\ \frac{E_{||}}{(-i\ k_{||})}\left(1 + \frac{\omega}{k_{||}\ v_e}\ Z\left(\frac{\omega}{k_{||}\ v_e}\right)\right) \tag{2}$$

where Z is the plasma dispersion function.

For electrostatic case, $\omega << k_{\|} v_e << k_{\|} v_A$ and we have

$$D \sim \frac{E_{\perp}}{-ik_{\perp}B} \sim \frac{T_e}{eB} \frac{n_1}{n_o} \quad . \tag{3}$$

By assuming $n_1/n_o \sim \frac{1}{16}$, we obtain

$$D = \frac{1}{16} \frac{T_e}{eB} \quad . \tag{4}$$

For plasmas with $\beta >> m_e/m_i$, we have $\omega \geq k_{\|} v_e >> k_{\|} v_A$ we have

$$\frac{n_1}{n_o} \sim \frac{eE_{\perp}}{T_e \; (-i \; k_{\perp})} \frac{v_e^2}{v_A^2} \quad . \tag{5}$$

The transport along the perturbed magnetic flux lines can be neglected, since $\omega >> k_{\|} v_e$. The diffusion coefficient is then given by

$$D \sim \frac{E_{\perp}}{(-i \; k_{\perp})B} \sim \frac{T_e}{eB} \frac{v_A^2}{v_e^2} \frac{n_1}{n_o} \quad . \tag{6}$$

If we assume the same numerical coefficient as the Bohm formula, we obtain

$$D \sim \frac{1}{16} \frac{T_e}{eB} \frac{v_A^2}{v_e^2} = \frac{1}{32} \frac{B}{e\mu_o n} \left(\frac{m_e}{m_i} \right) \tag{7}$$

where m_i is the ion mass.

Experimental results where the energy transport is dominated by the anomalous transport show that the diffusion coefficient given by the above formula is remarkably close to the experimental value. Dependence on magnetic field strength is obscured by neoclassical diffusion, and more experiments at lower densities are needed to test the dependence.

Turbulence with $\omega >> k_{\|} v_e$ scatters electrons strongly in the velocity space during the period of the bounce motion. Hence, the trapped electrons have a much larger effective collision frequency than the binary collision frequency. This may explain the absence of strong trapped ion modes.

In conclusion, a diffusion coefficient for turbulent plasmas in the mhd regime is derived based on an intuitive argument a la Bohm formula for plasmas in the electrostatic regime. The formula seems to fit the experimentally observed transport rates in tokamaks.

REFERENCES

1. D. Bohm, National Nuclear Energy Series, Division I, Vol. 5, Pages 1-12, 1949.
2. For example, see M. Murakami, Physics Today, Page 25, May 1979.

Work supported by Department of Energy, Contract DE-AT03-76ET51011, GA Project No. 3235.

1A2

LBL-10728

RESONANT DIFFUSION IN A WAVE OF EIKONAL FORM, AND ITS RELATION TO THE CHIRIKOV MAPPING*

Allan N. Kaufman, Celso Grebogi, Henry D.I. Abarbanel

Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720

A wave spectrum of moderate width can sometimes be represented as a single wave of eikonal form: $\phi(x,t)e^{i\psi(x,t)}$ + c.c. For example the Langmuir wave excited from noise by a beam can take this form. Such a wave has a spatially varying wave number $k(x)$ in a one-dimensional model. A particle with trajectory $x(t)$ moving in this wave sees a time dependent phase velocity $V_\phi(t) \equiv \omega(x,t)/k(x,t) \equiv -[\partial\psi(x,t)/\partial t][\partial\psi(x,t)/\partial x]^{-1}$. At those times, t_j, such that $V_\phi(t_j) = v(t_j)$, the particle <u>crosses</u> resonance, and the oscillation center experiences an impulse, dependent on its phase relative to the phase of the wave, $\psi_j \equiv \psi(x(t_j), t_j)$. Between crossings, the oscillation center is free, and the motion is <u>adiabatic</u> with respect to the wave field. To lowest order the formalism leads to results agreeing with quasilinear diffusion. Nonlinearly, the standard mapping of Chirikov appears.

The Chirkov mapping is then studied with the customary tools of statistical analysis. The oscillation-center velocity autocorrelation function is obtained numerically from a single orbit, for a range of values of the single parameter characterizing the mapping. The assumption of Markov behavior along the orbit is tested numerically for various lengths of time step and mapping parameter. The autocorrelation time and the Markov amnesia time are then compared to the inverse of the orbit instability rate, i.e., the Lyapunov-Kolmogorov-Sinai entropy.

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*Work supported by the Fusion Energy Division of the U. S. Department of Energy under contract No. W-7405-ENG-48.

Abstract submitted to 1980 Sherwood Theory Meeting, April 23-25, 1980

1A3

A THEOREM CONCERNING INDUCED SCATTERING IN PLASMA*

Shayne Johnston
Plasma Physics Laboratory
Columbia University
New York, New York 10027

A classical and general proof of the Manley-Rowe relations governing induced scattering in plasma is presented. The theorem is expressed in the context of the oscillation-center representation,[1] and relates the transfer of action between fields to the beat Hamiltonian of a resonant oscillation center. The proof of the theorem is facilitated by the power of the Lie transform formulation of canonical-transformation theory.[2] The significance of the theorem is that it provides a firm foundation for the oscillation-center approach to induced scattering, the virtues of which include the following:

(1) The notion of a beat potential with which particles resonate is formalized precisely;
(2) The isolation of the beat forces enables one to address the question of nonlinear saturation due to beat trapping;
(3) The linear action-transfer rate is proportional to the square of the modulus of the net beat Hamiltonian, a form which clearly displays both Debye shielding effects and the structure of a quantum transition probability;
(4) Since only second-order perturbation theory is required, a laborious calculation of third-order currents is completely circumvented.

The generality of the theorem extends to nonuniform and relativistic plasma. Two applications are presented. First, the general linear matrix element for a uniform plasma is explicitly derived; it describes induced scattering of waves in a relativistic magnetized plasma. Secondly, an analysis is given of the finite-length gain of a collective free-electron-laser amplifier operated in the stimulated Compton mode.[3] It is suggested that the plasma-modified Compton effect represents a new and viable regime for short-wavelength operation of such a device.

1. S. Johnston, Phys. Fluids 19, 93 (1976).

2. S. Johnston and A.N. Kaufman, Phys. Rev. Lett. 40, 1266 (1978).

3. S. Johnston, Bull. Am. Phys. Soc. 24, 663 (1979).

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* Work supported by U.S. Department of Energy Contract #EY-76-S-02-2456.

Quasilinear Diffusion and Convection in a Torus

S.M. Mahajan, R.D. Hazeltine, and D.A. Hitchcock

Fusion Research Center
The University of Texas at Austin
Austin, Texas 78712

Abstract

Relatively explicit expressions for the quasilinear convection and diffusion caused by low frequency electromagnetic fluctuations in a toroidal plasma are presented. The analysis is based on Kaufman's[1] description of resonant diffusion across phase-space surfaces corresponding to the three adiabatic invariants: μ, the magnetic moment, p_ϕ, the canonical angular momentum, and J, the toroidal flux linked by the drift orbit. Known properties of the expected form of the electromagnetic eigenmodes, together with explicit, small-gyroradius orbit equations, are used in an appropriate phase-space average to obtain transport coefficients analogous to those of conventional neoclassical theory. Among other conclusions, it is found that: (i) resonant diffusion in invariant space necessarily entails not only diffusion, but also radial convection, in coordinate space; (ii) transport coefficients are proportional to $|E_\parallel|^2$, rather than $|B_r|^2$, as noted previously for slab geometry; (iii) for far untrapped particles, the principal contribution to radial diffusion comes from diffusion across constant J, rather than constant p_ϕ, surfaces; (iv) deeply trapped particles can make a surprisingly important contribution to diffusion. The conclusions (i)-(iv) have not always been appreciated in the recent literature.

[1] A.N. Kaufman, Phys. of Fluids 15, 1063(1972).

This work is supported by the U.S. Department of Energy Contract DE-AC05-79ET-53036.

Stability of Drift and Trapped-Electron Modes in Tokamaks[*]

Liu Chen, C. Z. Cheng and M. S. Chance
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

The stability properties of drift and trapped-electron eigenmodes in tokamak plasmas are analyzed by means of the ballooning-mode formalism and are found to differ qualitatively with those predicted for a slab-model plasma.

The toroidal analysis reveals that the eigenmodes have two branches. In addition to the usual slab-like (Pearlstein-Berk) eigenmode branch, there is a new branch which is due entirely to the toroidal coupling. The slab-like branch, just as in the slab model, experiences finite shear damping because of its "anti-well" potential structure. The new toroidicity-induced branch, however, has negligible shear damping since its eigenmodes are quasi-bounded by the toroidicity-induced local potential wells.

These two branches have different stability characteristics. For the universal drift mode, we find that the eigenmodes of the toroidicity-induced branch can be destabalized, contrary to slab-model predictions; while the slab-like ones always remain stable. The toroidicity-induced eigenmodes for the trapped-electron mode are also much more unstable than the slab-like ones. Furthermore, finite $-\beta$ (electromagnetic) coupling to shear-Alfvén waves enhances the shear damping of the slab-like branch, but has little effect on the stability of toroidicity-induced branch.

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

ORAL presentation desired.

ORAL SESSION

FINITE-n BALLOONING-MODE THEORY FOR HIGH β TOKAMAKS

D. Dobrott and R. W. Moore

General Atomic Company
San Diego, California 92138

ABSTRACT

It has been predicted that if the pressure of a tokamak plasma is increased, the plasma will eventually become unstable to ballooning modes. Recently[1] it has been suggested that if one were to continue to increase the pressure, a "second" regime would be achieved which is stable according to the standard ballooning-mode analysis for very large, but finite, toroidal mode number n. However, equilibrium scale lengths decrease with increasing pressure and become comparable to perturbation lengths of the unstable mode, casting doubt on the finite-n ballooning-mode theory for high β.

Numerical, free-boundary FCT equilibria have been examined that mimic the analytic work presented by Ramos, *et al.*[1] The equilibria maintain circular cross-section on-axis and roughly the same aspect ratio as pressure is increased. Current density profiles that either vanish or are finite at the plasma-vacuum interface are investigated. Non-FCT, dee-shaped, free-boundary equilibria are also examined.

The range of flux surfaces found to be unstable to ballooning modes, as determined by the infinite-n theory, persists near the plasma edge as pressure increases in all cases. Analysis using the finite correction formula[2] for these equilibria indicates stability to ballooning modes for large-n values, as suggested by Charlton, *et al.*[3] Stable β of 4.5% is "achieved" by this process. However, the current gradient and perturbation scale lengths are comparable at these high pressures and the ordering for the correction formula used to obtain the above results is violated.

Kink effects that are insignificant for smooth current density profiles become large as increased pressure produces sharp current density gradients. This is confirmed by GATO stability calculations that indicate high β equilibria are very unstable to external kinks in the absence of conducting walls. Kink effects are retained in the finite-n analysis when sharp current gradients are taken into account. A new finite-n correction formula is obtained that indicates less stability than previously predicted. It should be emphasized however, that modest β is still possible with shape and current density profile optimization.

Work supported by Department of Energy, Contract DE-AT03-76ET51011, GA Project Agreement No. 3235.

[1] B. Coppi, A. Ferreira, J. Ramos, MIT Report PRR-79/10; H. R. Strauss, *et al.*, PPPL Report 1539, 1979; J. J. Ramos, B. Coppi, G. B. Crew, A. Ferreira, Bull Am. Phys. Soc. *24*, 962 (1979).

[2] E. A. Frieman, private communication (1978); J. W. Conner, R. J. Hastie, J. B. Taylor, Proc. Roy. Soc. A *368*, 1 (1979).

[3] L. A. Charlton, *et al.*, Phys. Rev. Lett. *43*, 1395 (1979).

1A7

n-Dependence of Ballooning Instabilities

R. L. Dewar, J. Manickam, R. C. Grimm, and M. S. Chance
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

The critical β for stability against ideal hydromagnetic internal ballooning modes as a function of toroidal mode number, n, is calculated for two different equilibrium sequences by use of a finite element technique ($n \lesssim 20$), and a WKB formalism ($n \gtrsim 10$). The agreement between the two methods is good in the overlap region $10 \lesssim n \lesssim 20$. The WKB formula reduces to the "1/n correction" at very high n, but is much more accurate at moderate n. The critical β vs n curves exhibit oscillatory structure at low n, but in both sequences the lower bound on β_c is set by $n = \infty$ modes at about $\beta_c \sim 5\%$. For reactor parameters, finite Larmor radius effects are not expected to have a large effect on this β limitation.

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Kinetic Theory of EBT Transport

M. Mond and Young-ping Pao
Courant Institute of Mathematical Sciences
New York University

Abstract

A systematic study of the EBT transport theory is carried out. The electric field $E = -\nabla\Phi_0(\psi) - \varsigma\nabla\Phi_1(\psi, \ell, \theta)$ is used. It is found that for plateau regime $\Phi_1 = \Phi_c \cos\theta + \Phi_s \sin\theta$ and the contributions of both terms are equally important.

Φ_c and Φ_s satisfy Fredholm integral equations. Banana regime is also discussed.

POSTER SESSION

MHD PROPERTIES OF ASYMMETRIC DEES

F. J. Helton and N. Ohyabu

General Atomic Company
San Diego, California 92138

ABSTRACT

Asymmetric dee-shaped plasma configurations are of considerable interest in view of their possible utilization in simplified divertor designs.[1] Asymmetric dee configurations are also of interest because of the novel numerics involved in their analysis. Possible plasma shapes of interest include dees with varying elongations and with an external separatrix bounding the plasma. We look at the ideal MHD properties of such configurations, particularly the effects of shaping and current profile modification on their stability. Comparisons are made with symmetric dee-shaped plasma configurations with small aspect ratio.

Work supported by Department of Energy, Contract DE-AT03-76ET51011, GA Project No. 3235.

[1] N. Ohyabu, "Expanded Boundary Approach to Impurity Control in Tokamaks," General Atomic Company Report GA-A15399 (1979).

1B3

The Tandem Tokamak[*]

M. S. Chance, H. P. Furth, A. H. Glasser[†], H. Selberg
Princeton University, Plasma Physics Laboratory,
Princeton, New Jersey 08544

An interesting contrast with the familiar case of the axially elongated 2-D tokamak is afforded by a hypothetical tokamak model of "dumbell-shaped" cross section, where an axially very extended 1-D mid-section is held in equilibrium (i.e., under tension) by appropriately shaped 2-D end sections. The equilibrium and stability conditions for the end sections are expected to call for non-Maxwellian features — hence the name "tandem tokamak." The present paper addresses only the long central region, where the field profiles depend on $r = r_0 + r_1$ $(-b \le r_1 \le a)$, but not on z. In order to preserve the "toroidal" feature, the equilibrium is obtained by solving the Grad-Shafranov equation for the poloidal flux in 1-D. The stability results are:

1) *Ideal MHD*. Stability against all modes can be demonstrated analytically by applying Rosenbluths' sufficient condition [1], which is satisfied for $rB_\phi \equiv$ constant. This model implies that $\beta_p \equiv 2p(0)/B_z^2(a) \sim 1$, so that $\beta = \beta_p\{1/[1+(B_\phi^2/B_z^2)]\}$ can be arbitrarily close to unity.

2) *Resistive MHD*. Kink/tearing-mode stability has been determined by numerical evaluations of Δ'. The $m = 0$ mode is most dangerous for $k_z \to 0$, but can be stabilized if the current profile is fairly flat and the wall is positioned within 0.5a of the plasma surface. This is in agreement with an analytical model. For $m \neq 0$ and with the same profiles, the wall must be brought to within 0.1a for stability. These observations are based on the sufficient condition $\Delta' \le 0$ at singular surfaces that fall into the outer half of the profile $(r_1 \ge 0)$. The actual stability condition $\Delta' \le \Delta_c$ is more lenient [2]. In particular, on the inner plasma side $(r_1 < 0)$, where $\nabla P \cdot \nabla B^2 < 0$, one expects Δ_c to be sufficiently large so as to stabilize resistive kink modes.

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[*] This work supported by the Department of Energy contract DE-AC02-76-CH03073.

[†] Permanent Address: Physics Department, Auburn University, Auburn, Alabama 36380

[1] Newcomb, W. A., Annals of Physics 10 (1960) 232.
[2] Glasser, A. H., Greene, J. M., and Johnson, J. L. Physics of Fluids 19 (1976) 567.

POSTER SESSION

1B4

A Numerical Study of Rf-heating in Deep Traps

D. Fyfe and I. Bernstein

We study the effect of rf-heating on the particle loss rate from deep traps by numerically integrating a steady-state bounce-averaged linear Fokker-Planck equation. The Fokker-Planck equation is solved in energy-magnetic moment coordinates using a Galerkin finite element procedure. We limit discussion to a single well in which the magnetic field and confining potential have their minimum and maxima at the same location. We use a geometric optics representation for the rf-fields. Rf-heating is applied at the positions in the well where the resonance condition is satisfied. We accomplish this by modifying the coefficients in the collision operator for those particles that can reach these positions. The calculation also can include passing particles in the loss region.

Kinetic Effects on the Ballooning Ion Temperature Gradient Drift Mode

P.W. Terry, W.C. Anderson, and W. Horton

Fusion Research Center
The University of Texas at Austin
Austin, Texas 78712

C.Z. Cheng

Princeton Plasma Physics Laboratory
Princeton, New Jersey 08544

Abstract

Linear toroidal mode theory predicts a strong fluid-like ion temperature gradient instability localized to the region of bad curvature. The mode rotates slowly in the ion diamagnetic direction and hence resonates with ion grad-B drifts. Using the drift kinetic equation for the ions we investigate how the resonances with the grad-B drifts modify the wave function and the dispersion relation from that previously given by hydrodynamic formulas. Modifications to the previously calculated nonlinear matrix elements $\varepsilon^{(2)}{}_{k_1,k_2}$ and $\varepsilon^{(3)}{}_{k_1,k_2,k_3}$ including the grad-B drifts are also given in anticipation of mode simulations including these resonant effects.

This work is supported by the U.S. Department of Energy Contract DE-AC05-79ET-53036.

1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

A QUASILINEAR THEORY FOR SPATIALLY NONUNIFORM PLASMAS*

C. E. Seyler
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

A formulation is presented for the quasilinear evolution equations for Vlasov plasmas for which one or more of the spatial coordinates is nonignorable in the averaged state. The basic assumption is that the usual spatial averaging operator applied to the Vlasov equation may be replaced by a phase space average over surfaces of constant single particle energy and momenta corresponding to the ignorable directions. The field equations are thus averaged over the ignorable directions. The resulting equations are then cast into a more useful form by expanding the first order distribution function in terms of eigenfunctions of the unperturbed Liouville operator. The final set of equations are of the form of diffusion equations in the energy and ignorable momentum variables. The usefulness of these equations remains to be seen, however, for the case of one nonignorable spatial coordinate it appears much can be done.

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

POSTER SESSION

DOUBLE TEARING MODE

Jae Koo Lee

General Atomic Company
San Diego, California 92138

ABSTRACT

The ideal MHD equation outside tearing layer(s) can be solved in a given geometry for various q (safety factor) profiles to provide the perturbed flux profile, $\psi(r)$ and the perturbed velocity profile. The knowledge of $\psi(r)$ then provides the stability criterion, the growth rate, and the saturation characteristics such as the magnetic island width and the poloidal magnetic field fluctuation level at saturation. Some of these techniques were used in the past for the study of the (single) tearing mode with a monotonic q profile[1,2] and for the double tearing mode[1] with a hollow q profile but with a simplifying assumption [i.e., $\psi(r) = 0$ for $0 \leq r \leq r_{s1}$ where r_{s1} is the location of the inner tearing layer] in the cylindrical geometry. This method has been applied to the study of the double tearing mode without the above assumption. The results for various hollow q profiles in slab or cylindrical geometry will be presented.

Work supported by Department of Energy, Contract DE-AT03-76-ET51011, GA Project No. 3235.

[1] H. P. Furth, P. H. Rutherford, and H. Selberg, Phys. Fluids *16*, 1054 (1973).

[2] B. Carreras, B. V. Waddell, and H. R. Hicks, Nucl. Fusion *19*, 1423 (1979).

THERMAL EQUILIBRIUM AND TIME EVOLUTION OF THERMAL INSTABILITIES

P. Rosenau and D. Degani
Energy Engineering Center, Dept. of Mechanical Engineering
Technion, Haifa, Israel

Steady state temperature and magnetic field profiles in a magnetically confined tokamak-type plasma are derived by balancing Ohmic, and non-Ohmic power input, thermal diffusion and radiation. We study the effects of electron conductivities, various sorts and levels of radiation and the effect of various events near the edge of the plasma (particles injection, light impurities and the presence of scrape-off layer). Particularly, we focus our attention on the influence of the aformentioned factors on the bifurcation of electric field and/or minor radius as a function of the temperature at the center. Points of bifurcation correspond to marginal stability with monotonically increasing (dcreasing) branch being stable (unstable). We examine parametrically the appearence and the "motion" of bifurcation points under the effects of conductivity, heating mechanism, radiation and various boundary conditions in order to understand their influence on the thermal stability. Critical values of parameters that cause an onset of a new branch or instability are determined. We find the possibility a "parametric window"; that is - between two branches there is a domain of temperatures at the center of which no equilibrium may exist. Also, as a rule radiation destabilizes the lower branch but it may have a partially stabilizing effect on the otherwise upper unstable branch. Finally a non-linear evolution in time of these states is considered.

1B9

THERMAL AND RADIATION LOSSES IN A LINEAR DEVICE

D. Degani and P. Rosenau
Energy Engineering Center
Dept. of Mechanical Engineering
Technion, Haifa, Israel

We study the non-linear effects of end plugs and radiation on the overall thermal losses in a θ pinch. The thermal response of the plug is simulated by calculating its non-linear convective transfer coefficient $h(T_e)$ that exhibits a different response to heating and to cooling. If the plug density is comparable to that of the plasma h scales as (k plug X Lplasma/K plasma X L plug) where K and L are the thermal conductivity and length, respectively. A more favorable scaling is obtained if the mass of the plug becomes comparable to the mass of the plasma. It is than possible to achieve ($h < 1$) a meaningfull reduction of thermal losses.

It is found that radiation modifies both quantitatively and qualitatively the later phase of electron temperature behavior. Bremstrahlung, for instance, may cause the appearence of a Thermal Cooling Wave that propagates from the exit toward the center of the column. A limit on the axial heat flux is mainly effective in slowing the initial phase of the thermal decay.

1B10

A METHOD FOR OBTAINING AREA-PRESERVING DISCRETE EQUATIONS (THE DISCRETE HAMILTONIAN METHOD)

C. R. Menyuk
Physics Department, UCLA

In r.f. heating and non-linear stability problems, it is often useful to replace the equations of motion for the individual particles with discrete equations. When non-area-preserving discrete equations are used, one generally finds particles moving stochastically even when the true motion is regular. Conversely, even fairly crude area-preserving approximations will predict the approximate threshold for stochasticity onset and regular motion below that threshold. A simple method for obtaining area-preserving discrete equations from the continuous equations of motion is discussed. This method is then applied to studying the superdiabatic motion of ions in mirrors[1] and particle heating in a wave propagating obliquely with respect to an imposed magnetic field[2].

[1] M. N. Rosenbluth, Phys. Rev. Lett.; 27, 135 (1971).

[2] G. R. Smith and A. N. Kauffman, Phys. Fluids; 21, 2230 (1978).

WAVE HEATING MODELS FOR
ION-CYCLOTRON HEATING IN EBT-S

J. L. Sperling, S. Hamasaki,
H. H. Klein, and N. A. Krall

JAYCOR, Del Mar, California 92014

ABSTRACT

Wave heating of ELMO BUMPY TORUS-SCALE (EBT-S) in the ion-cyclotron range of frequencies will be strongly influenced by the geometry of the plasma. In particular, the short finite length of the mirror sections means that the electron bounce frequency is of comparable magnitude to the ion-cyclotron frequency. Consequently, the bouncing motion of trapped particles impacts the electron absorption of wave energy. Furthermore, the varying magnetic field strength along magnetic field lines influences the ion-cyclotron absorption of waves because the ion-cyclotron resonance conditions are satisfied only at discrete points along the field lines. Expressions are given for trapped and passing electron absorption as well as ion-cyclotron absorption. A numerical example is also discussed.

Work supported under subcontract to McDonnell Douglas Astronautics Company.

1B12

A MODEL FOR ELECTRON RING FORMATION IN EBT

S. Hamasaki, H. H. Klein, N. A. Krall,
J. B. McBride* and J. L. Sperling

JAYCOR
1401 Camino Del Mar
Del Mar, CA 92014

In this paper we discuss a model for electron ring formation in EBT. The model uses relativistically correct heating rate, based on the quasilinear interaction of the electrons with the microwave electric fields, and includes detail propagation characteristics of microwaves in the background plasma and magnetic field. The steady state ring temperature, the radial extent of the rings, and thus the power required to sustain the rings are determined by balancing the line averaged heating rate against existing expressions for the classical energy loss processes of the ring electrons. We emphasize the roles of second harmonic heating in the formation of the rings and the role of relativistic effects in determining the steady state ring temperature.

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*Present address - Science Applications Inc., La Jolla, CA

PARTICLE AND ENERGY CONFINEMENT TIME FOR HILL'S VORTEX

Steven P. Auerbach and William C. Condit
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

Based on previous work,[1] we construct essentially exact solutions to the classical particle and heat transport equations for an elongated Hill's vortex equilibrium fueled at the vortex point. For a Hill's vortex with elongation λ(λ = ratio of axial to radial extent at the separatrix:$\lambda = 1$ for a spherical vortex) the particle and energy confinement times both scale as

$$\tau \sim \frac{\lambda^2}{1+4\lambda^2} R_o{}^2$$

where R_o is the vortex point radius. Thus, for a prolate vortex ($\lambda \gtrsim 1$) τ is almost independent of axial length, while for an oblate vortex ($\lambda < 1$) τ scales as the square of the axial length.

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

[1] Steven P. Auerbach, Bull. Am. Phys. Soc. <u>24</u>, 954 (1979).

POSTER SESSION

Resonant Parametric Excitations at the Plasma Edge in Lower-Hybrid Heating of Tokamaks

E. Villalón
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

The parametric decay of driven lower-hybrid pump electric field of finite spatial extent, into another lower-hybrid sideband field and a low frequency mode (e.g. an ion cyclotron wave) is studied, assuming that the magnitude of the pump is constant [1]. The stabilization of the resonant excitation due to a linear mismatch in wavenumbers produced by the density gradient, and to the Landau damping rates of the excited waves will be discussed using a WKB analysis, for both types of instabilities, temporally growing modes and spatially amplified solutions [2]. It is shown that either by increasing the strength of the mismatch K' or the spatial width of the pump L, the growth rate of the fastest growing normal mode decreases. When the excited waves are slightly damped, it is shown that there exists a finite value of the product $K'L$, such that above it no normal modes are excited. The spatial amplification factor is calculated as a function of the mismatch, damping rates, and of the spatial extent of the pump. The gaining length is found to be smaller than or equal to L, depending on the strength of the mismatch and damping rates. Calculations that apply these results to the excitation of ion cyclotron waves, near the plasma edge will be presented. The plasma conditions under which these waves may be excited will be discussed.

[1] A. Reiman, Phys. Fluids 21, 1000 (1978).
[2] E. Villalon, MIT Report PFC/JA-80-2.

*Work supported by U. S. Department of Energy Contract No. ET78-S-02-4682 and National Science Foundation Grant No. ENG77-00340

STRAIGHT LINE ORBIT STABILITY ANALYSIS OF MIRROR CONFINED PLASMAS FOR ARBITRARY ρ_i/R_p .*

J. R. Myra, P. J. Catto and R. E. Aamodt
Science Applications, Inc., Plasma Research Institute, Boulder, Colorado 80302

The stability problem for present-day mirror plasmas to azimuthally propagating modes ($k_\parallel = 0$) requires that ρ_i/R_p , the ratio of ion gyroradius to plasma radius, be treated as an order unity parameter. In general, for a gaussian density profile and a Maxwellian velocity distribution function, a complicated integro-differential equation results. In the limit of sufficiently large growth rates (straight line ion orbits) the integral equation may be approximated by a second order differential equation, similar in physical content to the straight line orbit limit of a matrix formulation previously obtained by Davidson.[1] Limiting cases are amenable to an analytical WKB analysis. When all ion guiding centers are on axis the results of Catto, Aamodt, Rosenbluth, Byers and Pearlstein[2] are recovered. In the slab limit, the lower-hybrid drift instability of local theory results. The transition between these two limiting cases is currently being investigated using a numerical shooting code. Results indicate a strong stabilizing effect when the guiding center spread exceeds the thermal gyroradius. A modified WKB analysis also enables an investigation of any possible modes associated with the lower hybrid fluid resonance, where the WKB potential is singular. When resonance occurs at only one radius in the plasma, no new modes are found.

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

1. R. C. Davidson, Phys. Fluids, 19, 1189 (1976).

2. P. J. Catto, R. E. Aamodt, M. N. Rosenbluth, J. A. Byers, and L. D. Pearlstein, SAI Report No. SAI-023-79-766LJ and to be published in Phys. Fluids (April).

1B16

Anomalous Transport due to Shear-Alfvén Eigenmodes*

W. W. Lee, M. S. Chance and H. Okuda
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

The existence of shear-Alfvén eigenmodes in a sheared slab has been confirmed using both a particle simulation code and a fourth-order shooting code. The eigenmodes have the tearing-type parity of odd ϕ and even $A_{\parallel}$, and are localized near the rational surface due to the finite Larmor radius effects as well as ion Landau damping. The shooting code results indicate that these modes are linearly damped and the damping rate decreases with plasma β. However, in the simulation, enhanced thermal fluctuations associated with these modes have been observed. These fluctuations, in turn, have produced a second-order eddy current near the rational surface. Theoretical analysis, based on the quasilinear treatment of the second-order drift kinetic equation, has been carried out and have verified its existence. Because of the presence of the eddy current, the shear-free region near the rational surface is widened. The saturation takes place when the zeroth-order current at the rational surface is completely nullified. Consequently, magnetic islands with several ρ_i's in width are formed which cause rapid electron energy transport across the rational surface. Similar results have been obtained for cases where inhomogeneities are introduced. We believe that this new mechanism will be very important in understanding anomalous transport processes in tokamaks.

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ORAL presentation desired.

1B17

VELOCITY-SPACE DEPENDENCES IN TANDEM MIRROR RESONANT TRANSPORT

Ronald H. Cohen
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

Resonant radial transport arises in tandem mirror machines due to non-axisymmetry in the transition regions at either end of the solenoid. Order-of-magnitude estimates have indicated that it could be the dominant loss channel in future machines. Here, it is shown that the pitch-angle dependence of particle radial drifts and the position of resonant surfaces in velocity space can have a significant impact upon transport and, under some circumstances, lead to lifetime values and scalings quite different than those given by the earlier estimates. These differences can be exploited in machine design. For example, if a finite rise ($\gtrsim$ 30%) in magnetic field strength is introduced between the solenoid midplane and the region where the non-symmetric (quadrupole) field components begin, large pitch-angle particles then mirror in an axisymmetric field. Operating parameters can be chosen so that resonant transport "self-quenches": a moderate flattening of radial profiles due to transport leads to the condition whereby particles satisfying the resonance condition are only weakly affected by the field asymmetry, thereby reducing the self-consistent radial particle flux to a value of order of the endloss current. Applications to TMX, a TMX upgrade, MFTF-B and reactors are discussed.

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

Oral or Poster; if Poster, please place next to "Some Factors Influencing the Radial Structure of Tandem-Mirror Plasmas" by M. E. Rensink and A. A. Mirin.

Abstract - 84206

1B18

SOME FACTORS INFLUENCING THE RADIAL STRUCTURE OF TANDEM-MIRROR PLASMAS

M.E. Rensink

Lawrence Livermore Laboratory
Livermore, California

A.A. Mirin

National Magnetic Fusion Energy Computer Center
Lawrence Livermore Laboratory
Livermore, California

We use a one-dimensional transport code to study the radial structure of the solenoid plasma in a classical tandem mirror. The motivation is to understand the global particle and energy confinement properties of a tandem mirror and to make detailed comparisons with available experimental data from TMX. Areas of concern are: (1) neutral gas penetration; (2) boundary conditions, especially on the radial electric field; (3) resonant heating of solenoid ions by instability-generated RF from the plugs; and (4) anamolous radial transport. A Monte Carlo neutral particle simulation package has recently been incorporated in the radial transport code. Results for TMX parameters indicate that multiple charge exchange is adequate to explain the observed gas penetration to the axis. Radial diffusion of resonant solenoid ions appears to be negligibly small in TMX, but anamolously enhanced diffusion is being examined with the code to identify experimentally observable signs of such transport.

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

Poster session preferred.
Place adjacent to R.H. Cohen, "Velocity Space Dependencies in Tandem Mirror Resonant Transport"

1B19

Effect of the High Energy Ion Tail on EBT Radial Transport*

E. F. Jaeger and C. L. Hedrick

Recent radial transport calculations[1] for the ELMO Bumpy Torus (EBT) show a parametric dependence on edge neutral pressure which is qualitatively similar to that observed for experiments in the collisionless electron regime. However, electron transport coefficients used in these calculations assume that the ambipolar potential well depth is large compared to the electron thermal energy, a condition which is not generally met in the solutions. When this assumption is relaxed, electron particle losses increase and the depth of the potential well becomes much less than that observed experimentally. Here we consider the approximate effect of a non-Maxwellian ion distribution on these transport solutions. When particle losses from a high energy ion tail exceed those from the bulk ions, the potential well is significantly enhanced. For example, when no ion tail is present as in the solutions of Ref. 1, potentials are on the order of the bulk ion temperature ($kT_i \sim 60$eV; $\phi \sim 60$V) for moderately collisionless electrons ($\nu_e/\Omega_{oe} \sim .6$). However, when 5% of the ions reside in a 400 eV tail, the potential exceeds 200 V and is approximately parabolic in shape for ad hoc temperature and density profiles in the tail which are also parabolic. In this case, a significant potential well is maintained even when the electron particle losses exceed the large electric field values.

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

[1] E. F. Jaeger et al., Phys. Rev. Lett. 40, 866 (1978); Nucl. Fusion 19, 1627 (1979)

1B20

Single Particle Drifts in Nearly Axisymmetric Magnetic Fields

H. Weitzner

Courant Institute of Mathematical Sciences

New York University

Abstract

We study single particle motion in static, nearly axisymmetric magnetic fields by the procedure of repeated canonical transformations of C.S. Gardner, Phys. Rev. 115, 791 (1959). We let ϵ be the particle larmor radius, which for high speed particles may not be too small, and we assume that the magnetic fields vary slowly relative to ϵ. We show how to carry out the construction of adiabatic invariants to all orders in a manner that preserves the canonical angular momentum in the axisymmetric case. The procedures changes accordingly as $B_p \sim B_T$, $B_p \sim \sqrt{\epsilon} B_T$, $B_p \sim \epsilon B_T$. We then add a non-axisymmetric field B_{nA}, e.g. divector or imperfection magnetic fields, where $B_{nA} \sim \epsilon B_T$. In the case $B_p \sim B_T$ we find thin banana orbits and the bananas drift slowly from one flux surface to the next. The change of canonical angular momentum and banana drift occur on the slowest time scale of the motion. In the other two cases, the banana orbits are fatter (in the parameter ϵ) and the angular momentum changes more rapidly than the slower drift off magnetic lines. In all cases Hamiltonians are given which characterize the particle drift across field lines and the critical points in the appropriate phase planes are described.

1B21

MHD STABILIZATION OF TOKAMAKS BY HELICAL FIELDS

J. P. Freidberg and P. A. Politzer
Massachusetts Institute of Technology

One important problem facing the tokamak program is to devise an effective means of controlling both major and minor disruptions. Based on experimental results from stellarators in Garching and Culham it is suggested that a possible method of solving this problem is by the addition of static helical fields on the basic tokamak geometry. To the extent that helical fields are an effective stabilizing mechanism, the crucial question is to determine how much helical transform is required. If the critical helical transform is sufficiently small it should be possible, at not too high a technological cost, to incorporate such fields in future large tokamaks.

We have addressed this problem theoretically as follows. Our basic assumption is that disruptions occur because of island overlap resulting from the growth of resistive tearing modes. In order to suppress disruptions we impose the conservative requirement that all resistive tearing modes be linearly stable. To ascertain the critical helical transform a marginal stability analysis is performed of the usual low β, large aspect ratio model of a tokamak $\beta \sim \varepsilon^2$, $B_\theta/B_z \sim \varepsilon$, $q \sim 1$, $\varepsilon \equiv a/R$. The model is modified to include helical fields in the equilibrium whose amplitude scales as $B_H/B_z \sim \varepsilon^{\frac{1}{2}}$. This ordering results in the helical transform $\iota\!\!\!-_H$ and the ohmic heating transform $\iota\!\!\!-_I$ both being of order unity. Our results show that the most unstable modes are $m = 2$, $n = 1$ and $m = 3$, $n = 2$ when the total transform on axis is held fixed at approximately unity because of internal kink modes. Several different profiles have been studied and our basic conclusion is as follows. For reasonable profiles all resistive tearing modes can be stabilized by a helical field under standard tokamak operating conditions $\iota\!\!\!-_I(a) \approx 1/3$ and $\iota\!\!\!-_I(0) + \iota\!\!\!-_H(0) \approx 1$. The critical helical transform for an $\ell = 2$ field is surprisingly small and is given by $\iota\!\!\!-_H(a)_{CRIT} \approx .15$. Detailed parameter studies have been made and will be presented at the conference.

1B22

ANALYSIS OF PROPERTIES OF THE MHD PARTICLE CODE

T. Tajima and F. Brunel

Physics Department, UCLA

The particle method of solving magnetohydrodynamic/hydrodynamic equations[1] has been successful and applies to many widely different circumstances with ease. By now we have developed a number of different versions of the code based on different algorithms[2] and we are in a position to analyze the basic properties of the code in a systematic way. When we allow the fluid to freely multi-stream, the fluid is described in terms of a collisionless Vlasov equation. Such code properties as sharpness of the spectra, dispersion of the modes, stability, and heating of particles for various versions of codes (Lax, Lax-Wendroff scheme; Nearest grid point, SUD, area weighting interpolation; FFT or finite differencing) are understood in a unified point of view ala Langdon[3]. A special feature of the code different from other fluid codes is, among other features, that this code can handle situations of multistreaming where others fail; an example will be given. On the other hand, the MHD particle code may also describe a "collisional" fluid when a collisional operator acting on the particles' motion is implemented.

[1] J. N. Lebeouf, T. Tajima, and J. M. Dawson, J. Comput. Phys., 31, 379 (1979).

[2] F. Brunel, T. Tajima, J. N. Leboeuf, and J. M. Dawson, Bull. Am. Phys. Soc., 24, 1007 (1979).

[3] A. B. Langdon, J. Comput. Phys., 6, 247 (1970).

Work supported by DOE and NSF.

POSTER SESSION REQUESTED.

1B23

CALCULATION OF IDEAL MHD GROWTH RATES IN FIELD REVERSED MIRRORS FOR THE SINGLE ADIABATIC AND DOUBLE ADIABATIC MODELS

D. V. Anderson, H. L. Berk, and J. H. Hammer
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

The observations of MHD stable compact toroids in many experiments contradict the predictions of ideal MHD theory. From the single and double adiabatic energy principles we are making detailed calculations of the growth rates and eigenfunctions obtained for the case of no toroidal field (appropriate for field reversed mirrors) and in the large toroidal mode number limit. We now routinely calculate the single adiabatic model for both analytical (Hill's vortex) and numerical (CYLEQ) generated equilibria. In limits explored by Newcomb we have complete agreement with his growth rates and eigenfunctions. The double adiabatic model, which allows tensor pressure in the perturbation, is now being included in the calculation. Looking ahead, we are formulating models which properly account for finite gyroradius effects or which solve cases having finite toroidal mode numbers. Our goal is to understand what feature of the kinetic theory stabilizes these configurations.

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

1. W. A. Newcomb, "MHD Instability in the Neighborhood of the Vortex Point of a Field-Reversed Magnetic-Mirror System," UCRL 83867, submitted for publication to Physics of Fluids.

POSTER

SATURATION OF THE LOWER-HYBRID DRIFT INSTABILITY*

Yu-Jiuan Chen & C. K. Birdsall
Electronics Research Laboratory
University of California
Berkeley, CA 94720

Bruce I. Cohen
Lawrence Livermore Laboratory
University of California
Livermore, CA 94550

Saturation mechanisms of the lower-hybrid drift instability in the low drift velocity regime ($v_d \ll v_{\text{thermal ion}}$) are studied both in a 1d particle-hybrid simulation and a nonlinear perturbation theory; v_d is the relative drift velocity between the electrons and ions. We find that ion trapping stabilizes the instability when v_d is kept constant, unless current relaxation ($v_d \rightarrow 0$) occurs via quasilinear diffusion. We also find a new saturation mechanism: a nonlinear ion orbit perturbation induces a frequency shift which is particularly effective in saturating long wavelength modes.

We use a one-dimensional slab configuration. In zero order, the ion pressure gradient cancels the equilibrium electric field force. In first order, the ions are treated as unmagnetized, and the electrons are assumed to respond to the wave linearly, because $\omega_{ci} \ll |\omega| \ll \omega_{pe}, \omega_{ce}$.

In simulation of small amplitude modes, there was good agreement of the linear growth rate, real frequency, and influence of finite beta effects associated with the nonresonant gradient B electron orbit modifications with linear theory. For large amplitude modes, at zero plasma beta and zero electron temperature, the simulations show that, when v_d is kept constant, the lower-hybrid drift instability is stabilized by ion trapping. When v_d is allowed to vary in time (for example, as a self-consistent consequence of momentum conservation), stabilization occurs as result of current relaxation with $v_d \rightarrow 0$, at a much lower level, a little below Davidson's prediction for $v_E/v_{ti} \lesssim 1$, as given by[1]

$$\frac{\mathcal{E}_s}{nT_i} = \frac{1}{8(1+\omega_{pe}^2/\omega_{ce}^2)} \frac{m_e}{m_i} \left(\frac{v_E}{v_{ti}}\right)^2 .$$

Analytic theory shows that a finite perturbation of the ion orbits leads to a nonlinear frequency shift that can stabilize the lower-hybrid drift instability. However, the resulting saturation level is small only for modes with wavelengths much longer than that of the most unstable mode. This result is obtained from a self-consistent solution of the Vlasov-Poisson equations using perturbation theory in which the nonlinear dielectric function and the nonlinear temporal evolution of a single unstable mode in the low drift velocity regime are calculated analytically.

*This research was supported in part by the Office of Naval Research under Contract N00014-77-c-0578, and in part by the Department of Energy under Contract No. W-7405-ENG-48.

[1] R. C. Davidson, Phys. Fluids 21, 1375 (1978).

Submitted for oral presentation.

POSTER SESSION

MACROSCOPIC STABILITY OF THE HOT ELECTRON ANNULUS IN EBT

R. L. Miller

General Atomic Company
San Diego, California 92138

ABSTRACT

We use guiding center theory with ($P_\perp >> P_\parallel$) to study the macroscopic stability of the hot electron annulus in the ELMO Bumpy Torus (EBT). Previous macroscopic stability studies of EBT have concentrated on localized modes. In this analysis, we employ a realistic geometry (a "bumpy" cylinder with a 2:1 magnetic mirror ratio), calculate numerical equilibria, and evaluate the second variation in the plasma energy (δW) using a finite element representation to identify the least stable mode of the plasma. We find that the plasma is unstable in this model for all values of the poloidal mode number, m, indicating that stabilization is required from two-fluid and/or kinetic effects even for m = 1.

Work supported by Department of Energy, Contract DE-AT03-76ET51011, GA Project No. 3235.

1980 Sherwood Theory Meeting

Analytical approximation of the non adiabatic particle response

T.J. Schep[+] and F. Pegoraro[++]

It is well known that a correct treatment of the non-adiabatic particle response is needed in the stability analysis of low frequency, drift-type modes. Therefore it is most interesting to generalize the results obtained in the plane slab model to a realistic toroidal configuration and to include effects such as those due to magnetic curvature and trapped particles. However, the non-adiabatic response is expressed in terms of complicated integrals over the particle orbits and this adds an intergral character to the differential equations that describe the mode behaviour in space and time.

Here we present analytic approximations of the kernel that relates the amplitude of the perturbed potential to the non-adiabatic particle response in an axisymmetric toroidal configuration. The plane slab model is explicitly recovered and the result compared with exact numerical calculations.

It is shown that in the plane slab as well as in toroidal geometry, the kernel contains a logarithmic singularity. This singularity is related to the behaviour of particles with vanishing parallel velocity so that, in toroidal geometry, it is related to the behaviour of trapped particles near their turning points. Besides this logarithmic term that describes the main contribution of resonant particles, the kernel contains a constant term arising from resonant as well as non resonant particles.

The analytic approximation we have obtained makes the dispersion relation of drift-type modes in toroidal geometry amenable to analytic as well as to simpler numerical calculation of the growth rate and of the spatial mode structure.

[+] Association Euratom-FOM, FOM-Instituut voor Plasmafysica,
Rijnhuizen, Nieuwegein, The Netherlands

[++] Scuola Normale Superiore, Pisa, Italy

PARAMETRIC STUDIES OF INSTABILITIES ASSOCIATED WITH RING DISTRIBUTIONS IN VELOCITY SPACE

Robert W. Huff, M. Ashour-Abdalla, J. N. Leboeuf,
J. M. Dawson, and C. F. Kennel
Department of Physics

A simulation study of electron cyclotron harmonic waves has been performed on the CHI computer. For the initial velocity distribution, we use a ring perpendicular to the ambient magnetic field, plus a cool Maxwellian component. Use of the CHI computer made it economically possible to carry out parametric studies, and thus understand the physics of the saturation mechanism, as well as its dependence on the initial conditions. At present we have identified cyclotron resonance as a saturation mechanism for very steep initial distribution functions. It appears, however, that for weaker initial distribution functions quasilinear velocity diffusion is responsible for saturation.

1B28

Fluctuations in Toroidal Geometry

D.A. Hitchcock, R.D. Hazeltine, and S.M. Mahajan

Fusion Research Center
The University of Texas at Austin
Austin, Texas 78712

Abstract

The toroidal quasilinear theory of Kaufman[1] is extended to the Klimontovich equation in an axisymmetric system. The resulting equations advance the electric field spectrum and the one particle distribution functions in time and exhibit a smooth transition between stable and unstable plasmas. Conservation laws and the H theorem are discussed and the relationship of this theory in a strongly stable system to neoclassical transport is examined.

[1] A.N. Kaufman, Phys. Fluids 15, 1063(1972).

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1B29

IRREVERSIBILITY AND TRANSPORT IN THE LOWER HYBRID DRIFT INSTABILITY*

J. F. Drake
Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20740

The dynamics of electrons in a low-frequency wave propogating perpendicular to a uniform magnetic field are studied and the implications of these results for transport and heating by the lower hybrid drift instability are explored. Below a threshold $e\phi/T_i \approx .25-.5$, all electron energy and momentum exchange with the wave are reversible and no plasma transport is possible. Above this threshold, trapping of electrons by the wave potentials takes place and causes irreversible electron heating and momentum exchange. In inhomogeneous plasma with weak drifts $v_{di}<v_i$ (diamagnetic velocity less than the ion thermal velocity) the lower hybrid drift instability saturates by ion trapping before this threshold is exceeded and no transport is possible. The saturation of the instability in this limit simply corresponds to the formation of flutes in the density profile. In the strong drift regime, the instability exceeds the electron trapping threshold and strong electron heating and transport accompany the saturation of the mode. Implications for understanding transport in reversed field theta pinches and mirrors will be discussed.

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SCALING OF THE CONFINEMENT PARAMETERS IN EBT*

Taner Uckan
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

An assessment of parameter and operating space of the EBT-I/S experiments has been carried out through a study of the simplified relationships between experimentally observable quantities and their theoretically predicted behavior. Although a sophisticated and self-consistent 1-D code[1] is available to calculate EBT transport, this study has proved to be useful for gaining insight into the relative dependences of the plasma parameters. For example, it may be shown that the plasma ambipolar potential well $\Delta\phi$ and the particle confinement time τ_p are related to the electron and ion temperatures and to the plasma density for a given microwave heating power level as follows:

$$T_e \sim \Delta\phi^{2/7}\ \tau_p^{4/7},\quad T_i \sim \Delta\phi/\ell n(\tau_p\Delta\phi),$$

and $n \sim \Delta\phi^{-2/7}\ \tau_p^{3/7}$, respectively. Here the confinement time is inversely proportional to the neutral density for $100 \leqslant T_e(\mathrm{eV}) \leqslant 600$, which is a typical temperature range for EBT-I/S.

The calculations presented here are based on neoclassical scaling, experimental observations and theoretical predictions of the confinement parameters. Namely, almost flat temperature and density profiles and a nearly quadratic potential well are assumed. For the transport model, the electrons are taken to be nonresonant while ions are in the resonant (plateau) regime. For both species Spong's[2] transport coefficients are employed in conjunction with particle and energy balance equations and the ambipolarity condition. Also presented are temperature and density scaling with the operating base pressure, taking into account the experimental observations of the scaling of the potential well and the particle confinement time.

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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 et al., Phys. Rev. Lett. 43, 855 (1979).

[2] D. A. Spong et al., Nucl. Fusion 19, 665 (1979); D. A. Spong and C. L. Hedrick, "Variational Corrections to EBT Neoclassical Ion Plateau Transport", submitted to Phys. Fluids.

PARALLEL ELECTRON KINETIC EFFECTS AND ELECTROMAGNETIC COUPLINGS FOR MIRROR-MACHINE MICROINSTABILITIES*

Gary R. Smith and William M. Nevins
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

We are attempting to improve mirror-machine microstability theory by including parallel kinetic effects due to non-zero electron temperature T_e. First, we recall the form of the kinetic effects in the homogeneous-plasma model, assuming the ion response is electrostatic but retaining all electromagnetic couplings present in the 3 x 3 dielectric tensor.[1] The kinetic effects generally lead to a dispersion relation complicated by appearance of the plasma dispersion function Z'. However, the strong inequality $\omega_{pe} >> kc$ usually holds for the "loss-cone" modes and for the densities that occur in present and future mirror machines. That inequality, together with other well-satisfied inequalities, leads to a cancellation of the perturbed, parallel electrostatic field $-\partial\phi/\partial s$ by the parallel component of the perturbed, inductive electric field.[2] As a result, Z' disappears from the dispersion relation, which implies that effects of non-zero T_e are negligible even if the parallel phase velocity $\omega/k_{\parallel} \sim (T_e/m_e)^{1/2}$.

Second, we consider the same kinetic effects and electromagnetic couplings for a plasma with inhomogeneity along the magnetic-field direction. A normal-mode equation similar to the homogeneous plasma dispersion relation is derived. In the limit that the midplane value of $\omega_{pe}/kc >> 1$, kinetic effects are only important in low-density regions at the ends of the plasma.

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

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POSTER SESSION

Effect on the tearing mode growth rate due to the presence of a stochastic magnetic field*

B. A. Carreras, M. N. Rosenbluth
Institute for Advanced Study, Princeton, New Jersey 08540

H. R. Hicks
Oak Ridge National Laboratory, Oak Ridge, TN. 37830

ABSTRACT

We have studied the effect on the growth of a tearing mode due to the presence of a stochastic magnetic field. An analytic solution is given for the case in which the stochastic magnetic field is static. In that case, an unstable tearing mode is further destabilized (stabilized) if the Δ' of the modes nonlinearly driven are positive (negative).

In the limit in which few modes are present, we compare the analytic calculation with numerical results. This offers a simple interpretation of the destabilization of the $(m = 3; n = 2)$ tearing mode by the $(m = 2; n = 1)$ modes, which was previously observed in numerical simulations of nonlinear interaction of tearing modes.[1]

When the stochastic magnetic field is not static, we present numerical results which suggest the dominance in this situation of an anomalous dissipative mechanism.

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*This work was supported by the United States Department of Energy Contract Nos. DE-AC02-76ET, 53011, A003, W-7405-eng-26.

[1] B. V. Waddell, et al., Phys. Fluids 22, 896 (1979).

ABSTRACT

Fluid Turbulence Model of Disruptive Instability in Tokamaks*, D.J. Tetreault, M.I.T. -

A fluid turbulence model of the disruptive instability based on the resistive MHD equations describing low mode number tearing modes is presented. The model conserves both energy and helicity, and predicts both mode coupling and turbulent dissipation. The dissipation takes the form of anamalous resistivity and viscosity due to the self-consistent stochastic magnetic fields. In the presence of magnetic shear, the dissipation is proportional to the magnetic field line diffusion coefficient. The anomalous resistivity becomes nonzero at magnetic island overlap, and enhances the tearing mode growth rate. Subsequent to island overlap, the ensuing mode coupling and dissipation cascade energy to small scales and poloidal flux to large scales. This process causes the magnetic field stochastic region to encompass the plasma cross section in a characteristic time, $\tau_R(\tau_H/\tau_R)^{2/3}$, where τ_R is the resistive time and τ_H is the toroidal Alven time.

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Integral Equation Formulation of Collisionless Reconnecting Modes*

B. Chike-Obi, G. Crew, T.M. Antonsen Jr. and B. Coppi

Massachusetts Institute of Technology
Cambridge, MA 02139

We analyse the linear stability of collisionless reconnecting modes in high temperature plasmas. For realistic values of ion temperature and electron temperature gradients the mode amplitude varies on a scale length of the order of the ion gyroradius[1] and consequently the mode structure must be determined by an integral equation[2]. In particular, near the singular surface the ion response is adiabatic. Solution of the integral equation in a low β plasma indicates the presence of two modes (with perpendicular phase velocities in the electron and ion diamagnetic drift direction), and a stabilizing effect associated with the perturbed electrostatic potential is found.

The problem is reformulated for the case of a finite β plasma. In this case it becomes necessary to reexamine the boundary conditions applied to the inner solution and determine their effect on the parity of the mode about the singular surface.

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[2] T.M. Antonsen Jr. and B. Coppi, MIT/RLE Report PRR 79/23, submitted to Phys. Rev. Lett.

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1B35

SCALING CHARACTERISTICS OF HOT ELECTRON RINGS IN EBT*

N. A. Uckan

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

In EBT a steady-state plasma is sustained and heated by ECH. The key element of this concept, derived from the ELMO mirror experiments, is the high-beta, hot electron ring (annulus) formed in each sector of the torus. The existence of stable equilibrium for these hot electron rings and the ability to sustain them with sufficiently low amounts of microwave power are central to the successful operation of EBT's.

The physical mechanisms that influence ring formation and heating, equilibrium and stability requirements, and ring-core interaction determine the scaling characteristics of the rings and the optimal behavior of EBT plasmas. Although the parameter range accessible in past (ELMO) and present experiments (EBT-I/S, NBT) are modest, good agreement between theory and experiment exists.[1] Favorable ring scaling has been observed by the variations between EBT-I (18 GHz, $B_{res} \simeq 6.5$ kG) and EBT-S (28 GHz, $B_{res} \simeq 10$ kG). In EBT-S the ring temperatures ($\sim$500 keV) are about three times higher than in EBT-I ($\sim$150 keV) for comparable ring plasma densities ($\sim 2\text{-}3 \times 10^{11}$ cm^{-3}) and ring sustaining power ($\sim$5-10 kw), and stable toroidal core operation has a broader range than observed in EBT-I. Because of significant uncertainties in the ring volume scaling and in detailed understanding of ring-core coupling, parametric analysis indicates the strong influence of scaling parameters and assumptions on the boundaries of possible operating space and on the reactor performance. However, favorable reactor performance can be obtained by scaling the ring sustaining power from ELMO → EBT-I/S → EBT-P → EBT-R using the constancy of the dimensionless parameters. Projections for EBT-P and reactor plasmas will be given.

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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] N. A. Uckan, editor, *EBT Ring Physics, Proceedings of the Workshop*, (Oak Ridge, Tennessee, December 3-5, 1979) CONF-791228.

Energy Scaling of Runaway Transport by Magnetic Microturbulence: Comparison of Theory and Experiment*

H. E. Mynick
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

As shown in previous work,[1] the large gyroradius and perpendicular drifts of runaway electrons can enable them to average over the mode structure of magnetic microturbulence, thereby causing the turbulence to be considerably less effective as a transport mechanism for runaways than for thermal electrons, which may be treated as driftless. The present work considers this scaling of an electron's confinement time τ in microturbulence with energy E in more detail, and compares the explicit results coming from theory with experimental runaway data recently compiled[2] from a number of tokamaks. The scaling of τ with E depends on a number of parameters characterizing the turbulence, the most important of which are the relative proportions of modes in the turbulence having even or odd parity about their rational surfaces, and the typical radial width of one of these modes. For reasonable values of these parameters, the agreement between theory and experiment is suggestive that the transport is controlled by stochasticity due to the magnetic turbulence.

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2. H. E. Mynick and J. D. Strachan (to be published).

Effect of Plasma Diffusion on Mirnov Oscillations

D. Biskamp

Max-Planck-Institut für Plasmaphysik
8046 Garching bei München

The theory of rotating magnetic islands (Mirnov oscillations) in a cylindrical plasma as given recently1) is generalized by taking into account plasma diffusion. Instead of the density being a flux function $\rho = \rho(\psi)$, ρ has a finite gradient within the islands depending on the diffusion coefficient κ and the island width. For large κ one finds $\omega = \omega_*$ due to $\rho = \rho_o(r)$. Here $j = j(\psi)$, just as in the case of negligible diffusion1). The magnetic islands are symmetric and $\tilde{B}_\theta(t)$ at the plasma edge is sinosoidal. For intermediate values of κ conditions are more complex, $j \neq j(\psi)$; the islands are distorted and $\tilde{B}_\theta(t)$ has strong harmonic components. In this case ω is smaller than the original value of ω_* due to flattening of the density profile and to generation of an electrostatic double layer leading to local rotation of the plasma in the ion diamagnetic direction. The latter effect is the stronger, the smaller the ion viscosity. Large islands in general rotate at a smaller frequency than small ones. The island width, however, is only determined by the average current profile and the behaviour of the resistivity. The penetration of external helical magnetic perturbations is also investigated. It leads to standing magnetic islands for amplitudes above a certain threshold which depends on the size of the spontaneously generated rotating islands. The results are confirmed and made quantitative by numerical solutions of the two fluid equations1) in 2D helical geometry.

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Summation of Oscillation-Center Expansions*

E. Rosengaus and R. L. Dewar
Plasma Physics Laboratory, Princeton University
Princeton NJ 08544

Using the exactly soluble [1] case of a particle in a sinusoidal potential as a test case, we are examining schemes for extending oscillation center theory to treat the scattering of particles by waves. A primitive perturbation expansion of the Hamilton-Jacobi equation using the free-particle propagator can be easily extended to high order; it seems to be absolutely convergent outside of the trapping region. In order to extend the theory to this region, we must renormalize the expansion; several approaches to this problem have been attempted. The use of resonance-broadened Green's functions rapidly becomes impractical, even using MACSYMA. Analytic continuation of the primitive series by use of an integral representation [2] seems a practical approach. We discuss the properties of the complex canonical transformation induced by the analytic continuation procedure.

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

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GUIDING CENTER ORBITS IN MFTF-B PLUG AND A-CELL

J. A. Byers and L. D. Pearlstein
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

We use the guiding center drift equations in an α, β coordinate system ($B = \nabla\alpha \times \nabla\beta$) to scan the drift orbits for MFTF-B, with particular focus on the extreme orbits in the A-cell. The vacuum magnetic field is obtained from actual field lines of present designs. Finite beta plasma fields are an essential feature; we include simple models for the self-B field and ambipolar potential, with only rough approximations for the radial variation. We also use the long thin approximation to simplify the calculation even though in the A-cell this is only marginally valid. In the plug we find only a small fraction of the ions with banana orbits; most of the ions drift close to the flux surfaces and hence omnigenity appears to be a good assumption. In the A-cell, in the vacuum fields alone, the orbits are known to be quite extreme; while the orbits are closed they extend out to a large radius, 2.5 - 3.0 meters, for virtually all initial conditions. Also, the long thin approximation breaks down for such extreme orbits at large radii. With finite beta fields we find that a large class of ion orbits can remain close to their initial flux surfaces; but, other ion orbits, including the sloshing hot ions required for DCLC stability, are similar to their vacuum field orbits. This occurs despite strong self fields because of cancellations between the $\underline{B} \times \nabla\phi$ drift and the $\underline{B} \times \nabla B$ drift. The hot (200 keV) electrons on the other hand, have the various drifts adding with the result that these hot electrons are nearly omnigeneous. These results are strongly dependent on the choice of plasma fields.

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1B40

MHD STABILITY OF EQUILIBRIA WITH FLOW

R. V. Lovelace

Department of Applied Physics,
Cornell University, Ithaca, N. Y. 14853

A study has been made of the MHD stability of equilibrium configurations with flow $\underset{\sim}{v}(\underset{\sim}{x})$. The approach is in terms of the Lagrangian perturbations of the physical variables as discussed previously by Frieman and Rotenberg and by Lynden-Bell and Ostriker. For example, $\Delta\underset{\sim}{v} = \delta\underset{\sim}{v} + (\underset{\sim}{\xi}\cdot\underset{\sim}{\nabla})\ \underset{\sim}{v} = (\partial/\partial t + \underset{\sim}{v}\cdot\underset{\sim}{\nabla})\ \xi$, where Δv $(\delta\underset{\sim}{v})$ is the Lagrangian (Eulerian) velocity perturbation, and ξ is the Lagrangian displacement of a fluid particle. The linearized equation for $\underset{\sim}{\xi}$ has the form $\varrho\ (\partial^2/\partial t^2)\underset{\sim}{\xi} + 2\varrho(\underset{\sim}{v}\cdot\underset{\sim}{\nabla})(\partial\underset{\sim}{\xi}/\partial t) = \underset{\sim}{F}(\xi)$, where $\underset{\sim}{F}$ is a self-adjoint operator on $\underset{\sim}{\xi}$. Detailed stability results have obtained for the class of equilibria with $\underset{\sim}{v} = (\alpha/\varrho)\underset{\sim}{B}$, where α and the density, ϱ, depend only on the flux function $\psi(\underset{\sim}{x})$, and where α^2/ϱ = const. For this class of equilibria a comparison can be made between the stability of a static equilibrium ($\underset{\sim}{v} = o$) with a given field configuration and an equilibrium with flow ($\underset{\sim}{v} \neq o$) which has the same field configuration but a different scalar pressure.

1B41

Tearing Mode with Negative Δ'

X.S. Lee, S.M. Mahajan
R.D. Hazeltine, and D.W. Ross

Fusion Research Center
The University of Texas at Austin
Austin, Texas 78712

Abstract

The shear Alfvén tearing mode, which generalizes the well-known m = 1 internal kink mode[1] and has the same dispersion relation ($\omega = i\pi k_{\parallel}' V_A |\Delta|^{-1}$), is found to be always unstable for $\Delta' < 0$ in the $k_{\perp} \to 0$ limit regardless of collisionality, shear, and beta. However, in contrast to micro-tearing modes, this fast growing mode does not occur when $\Delta' + 2k_{\perp} = 0$. The effects of increasing $k_{\perp}$ on this potentially important mode is examined both analytically, using a previous variational theory[2], and numerically. It should be noted that this mode lies on the same branch of the slab model dispersion relation as all other unstable tearing modes, and thus fits into the unification scheme presented previously[3].

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IMPLICATIONS OF RECENT MATHEMATICAL RESULTS FOR FLUID FLOW SIMULATION*

Yvain M. Treve**, La Jolla Institute

ABSTRACT

Our work on an MHD extension of the Bénard problem has revealed that most Galerkin approximations (= spectral representations = truncations) to the exact solution that have been used for the hydrodynamic Bénard problem are deficient in three important respects: 1) the modes are selected in ways which do not even guarantee qualitatively correct behavior; 2) uniform spatial resolution of the fields is not achieved; 3) exchanges between the total mechanical, potential and internal energies do not take place at the rates imposed by the equations of the model.

From the work of several mathematicians, notably Ladyzhenskaya[1] on the Navier-Stokes equation correct qualitative behavior of the Galerkin approximation is guaranteed provided all modes $f_{m,n}$ are retained whose eigenvalues satisfy the inequality $\lambda_{m,n} < C\,Re^2$, where C depends on the volume occupied by the fluid, and Re is the Reynolds number. Uniform spatial resolution is thereby automatically achieved.

The value of the constant C is difficult to determine a priori but it should be possible to estimate it through numerical experimentation.

Correct simulation of the energy exchanges can be obtained by using another selection rule which completes Ladyzhenskaya's. Work is in progress for the extension of this rule to the MHD version of the Bénard problem.

MHD codes presently in use may suffer from the defects pointed out above and others related to mass and charge transfer. They could perhaps be cured analogously.

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** Mailing address: 125 San Rafael Ave., Santa Barbara, Ca. 93109

[1] Ladyzhenskaya, O.A., Sov. Phys. Dokl., 17, No. 7 (1973) 647-649; See also J. Sov. Math., 3 (1976) 458-479.

1B43

Anomalous Transport and the "Principle of Profile Consistency"

Bruno Coppi

Massachusetts Institute of Technology

Starting from global constraints (conditions for macroscopic stability, energy and particle balance, etc.) for the spatial distributions of the current density, the electron temperature and the particle density, a simplified model of the electron thermal energy and particle transport, that reproduces the results of a relatively large class of experiments, has been formulated. The electron thermal transport is assumed to result from a diffusion process and the form of the relevant coefficient D^e_{th} is deduced from the observation that in ohmically heated relatively low density plasmas, the electron temperature profile is nearly Gaussian, while the loop voltage $V_{||}$ is nearly constant. Thus we find

$$D^e_{th} \simeq \frac{1}{64} \frac{J_*(r)}{ne} \times \frac{3}{\pi} a \frac{q_s}{q_o} \times \frac{eV_{||}}{\alpha_D T_e} \frac{4a}{R}$$

where $J_*(r) = I_{||}(r)/(\pi r^2)$, $I_{||}(r)$ being the total plasma current, while

$$\frac{eV_{||}}{\alpha_D T_e} \frac{4a}{R} = \varepsilon_d C^{2/5}_{i,e}$$

ε_d is a numerical constant and $C_{i,e} = D_\eta \omega_{pi,e}/V^2_{the}$ is a dimensionless number characterizing the microscopic reconnection processes that are assumed to underlie the form of D^e_{th}. The constant ε_d is estimated from the experiments to be about 0.3 for $C_{i,e} \equiv C_i = D_\eta \omega_{pi}/V^2_{the}$ while the exponent of $C^{2/5}_{i,e}$ in Eq.(2) is chosen by the criterion that it has the same dependence as $1/T_e(r)$. In addition α_D is a weak function of r/a that is close to unity, $D_\eta = \eta_{cl} c^2/4\pi$, and η is the classical electrical resistivity.

The particle transport is assumed to be the result of an outward diffusion, with a coefficient $D_p \propto D^e_{th}$ and of an inward particle flux Γ_{in} that does not depend on the gradients of either n or T_e. In particular Γ has a form that leads to reproduce the observed particle density profiles[1] and that make all the terms entering the electron thermal energy balance equation have a mutually consistent radial dependence.

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1B44

STABILITY OF THE FIELD REVERSED MIRROR

Edward C. Morse
Department of Nuclear Engineering
U.C. Berkeley, Berkeley, CA. 94720

The stability of the field-reversed mirror has been analyzed using a variational technique, treating the ions as a Vlasov system. A variational development based on a 2 1/2 dimensional electromagnetic simulation code, SUPERLAYER, has yielded information on the stability of an axisymmetric field-reversed mirror for a case where the ion gyroradius is on the order of the system size.

Instabilities for modes of form $e^{i\ell\theta}$, where $\ell = \theta, 1,2$, have been analyzed. A simple model of the instabilities is shown, which gives insight into the physical mechanism for instability and also into the adjointness property of the operators involved.

1B45

A MOMENTS APPROACH FOR THE FLUX SURFACE SHIFT IN TOKAMAKS*

L. L. Lao
R. M. Wieland
W. A. Houlberg
D. J. Sigmar

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

We obtain a computationally fast method for determining the flux surface shift in an elliptic plasma by taking the first moment of the current density in the equilibrium equation. At first, the elongation of the flux surfaces is assumed to be uniform over the plasma cross section. With this method, given the pressure and toroidal current profiles, the shift can be quickly calculated from a second order non-linear ordinary differential equation. For low β, the equation for the shift can be linearized and solved analytically. The analytic solution is similar in form with the familiar Shafranov shift formula but with correction factors due to elongation. For high β, the equation is solved numerically. The results agree well with those obtained from using the full 2-D equilibrium codes. This fast method of calculating the shift is particularly appealing to transport simulations of non-circular, high β plasma which require a fast (possibly "on line") and accurate description of the evolution of plasma volume and flux surface shifts. The extension of this method to include the elongation self-consistently is straightforward and presently underway.

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Scaling of Energy Confinement Time: Error Estimates and Dependence on Plasma Temperature

D.Düchs, D.Pfirsch, A.Schlüter
MPI f.Plasmaphysik, 8046 Garching, F.R.Germany

Since theory does not reliably predict plasma confinement, statistical methods using experimental results must be applied to obtain empirical τ_{eE}, the electron energy confinement time, for future tokamaks.

Several such empirical formulae are found in recent literature (e.g. [1]). We revisit $\omega_g \cdot \tau_{eE}$ as power product of β, r_g/a, R/a, λ_{mfp}/a, q (with their usual meaning), staying within Fokker-Planck theory but neglecting Debye-shielding effects.

The data of the ensemble are screened with respect to their deviation from τ_{Ohm}, using Spitzer conductivity. For the resulting data set a correlation matrix and a correlation vector are defined while calculating the minimum quadratic error. All relevant information from the data is contained in this matrix and vector. Their features are investigated and exploited to obtain

a) an optimum set of exponents of the above basic quantities,

b) internal relations between these,

c) consistent variations of the exponents (rescaling). For example, the temperature dependence cannot be inferred from pure ohmic heating experiments; then, for any (additionally given) dependence on T, all other optimum exponents can be obtained;

d) consistent error bars of exponents for prescribed error margin in τ_{eE}.

The optimum scaling exhibits a temperature dependence similar to the Coppi-Mazzucato scaling [2]. Numerical examples extrapolating to JET, ZEPHYR and INTOR parameters are given.

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1980 SHERWOOD THEORY MEETING
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A RESISTIVE HYBRID-KINETIC MODEL*

J. P. Mondt
Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico 87545

In view of the recognized importance of resistive instabilities for transport and stability, it is of interest to investigate the effects of finite ion gyroradius on such modes, which often are very localized.

To this end the hybrid-kinetic formalism (Vlasov ions, guiding-center electrons)[1] has now been generalized to include the effects of (constant) resistivity on electromagnetic modes of low frequency ($|\omega| \lesssim \omega_{ci}$). Also included is a gravitational potential to simulate toroidal field curvature effects. Resistivity is assumed to be entirely due to collisions of electrons with ions, and only enters through generalized Ohm's law. On the other hand, gravity only affects the full momentum balance equation.

In calculating ion momentum density and pressure terms therein, we assume $|\omega| >> \omega_{\text{ion defl}}$, i.e., Vlasov ions. On the other hand a BGK-model[2] for electron-ion collisions in the electron kinetic equation is used to calculate the electron pressure contribution to momentum balance.

We note that this procedure implies the assumption

$$r_{Li}|\omega| >> V_r \quad ,$$

where V_r is the resistive speed.

An integro-differential eigenvalue equation for the perturbed vector potential is derived. This equation exhibits, a) the importance of nonresonant FLR effects on local resistive modes, b) the importance of resonant FLR effects associated with field curvature.

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

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Electric Field Effects on Lower Hybrid Heating and Current Generation in Versator II*

R. Englade, T. Antonsen, M. Porkolab, and N. Sharky
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

At the 1979 Sherwood Meeting we reported on a one-dimensional transport code simulation of the plasma heating and current generation that might result from the lower hybrid RF experiment being prepared for Versator II.[1] Our calculations neglected the effect of the toroidal electric field on the electron distribution function. In this paper we propose a method for including the toroidal electric field effect in the presence of a spectrum of lower hybrid waves. Suppose V_2 is the maximum parallel phase velocity of the wave spectrum and V_D is the Dreicer velocity at a given radius when the RF power is turned on. For parallel electron velocities $V_{||} < \max (V_2, V_D)$, we obtain an analytic solution of a one dimensional relativistic Fokker-Planck equation for the electron distribution function that includes quasi-linear diffusion, the electric field term, a collisional term, and a source term. For $V_{||} > \max (V_2, V_D)$, the "runaway" region, we solve a simplified equation containing the electric field term and a phenomenological runaway loss term. We match the two solutions at $V_{||} = \max (V_2, V_D)$.

Incorporating this method into our transport code, we follow the time development of electron temperature and plasma current for various combinations of model parameters.

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[1] R. Englade, T. Antonsen, and M. Porkolab, Paper 2C5, 1979 Sherwood Meeting, Mt. Pocono, PA.

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

1C2

A Theory of Modular Stellarators

J. A. Derr and J. L. Shohet
University of Wisconsin, Madison, WI 53706*

The classical helical stellarator is composed of two separate coil systems. A set of toroidal field coils provides the main toroidal field, and a set of helical coils provides the poloidal field which produces the rotational transform characteristic of the stellarator field. The stellarator requires a minimum of two helices, wound in the same rotational sense, with currents in opposing toroidal directions. Thus the helices produce no net toroidal or poloidal current.

We have discovered a new stellarator configuration which eliminates the need for the toroidal field coils. This stellarator consists of two helices wound with opposing poloidal rotation. The helical currents flow in opposite toroidal directions, as in the classical stellarator. Thus this helical system has no net toroidal current, but possesses a net poloidal current, which produces the toroidal field. Such a configuration will produce closed, nested toroidal flux surfaces with significant rotational transform and shear if the helics are wound with different pitch angles. For example, we have computed flux surfaces for an $\ell = 3$ stellarator wound according to the law:

$$\theta_1 = \frac{3}{5} (\phi - \pi) \qquad (1)$$

$$\theta_2 = \frac{-3}{10} \phi \qquad (2)$$

θ_1 and θ_2 are the toroidal angles of the two helices as a function of the poloidal angle ϕ.

A mapping of the helical system onto the $\theta - \phi$ plane shows that the conductors may be represented piece-wise by a set of triangular functions displaced poloidally and toroidally. We may thus represent the helical system through a corresponding set of Fourier series expansions. Modularity is formally obtained through truncation of these series. We present results of magnetic surface studies for these modular configurations, discussing the relationship of important surface properties with the bandwidth of the Fourier series representation.

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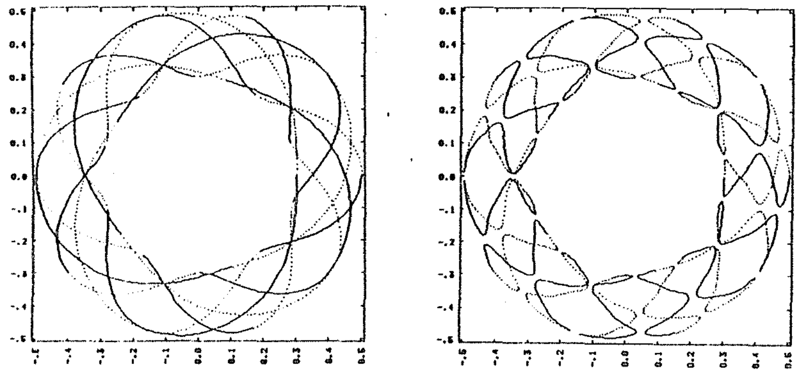

$\ell = 3$, M = 5 continuous helical stellarator (left) and two-term modular equivalent (right).

SLOSHING IONS IN TANDEM MIRROR A-CELLS

T. A. Cutler and M. E. Rensink
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

We investigate the generation and maintenance of ion density profiles which are peaked off the midplane of a magnetic mirror cell. The sloshing ion distribution may be generated either by the injection of energetic ions at some acute angle to the magnetic field in the midplane of the cell, or by perpendicular injection at some point off the midplane. Charge-exchange pumping of ions trapped near the bottom of the potential well maintains the density depression at the midplane. Ion distribution functions are computed via a bounce-averaged Fokker-Planck code which incorporates the beam injection and pumping geometries, a self-consistent ambipolar potential, and barrier filling due to passing (untrapped) ions. Applications to the proposed MFTF-B and TMX-Upgrade experiments will be given.

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POSTER SESSION

Three Dimensional Equilibrium and Transport in EBT

W. H. Miner* and N. K. Winsor
Naval Research Laboratory, Washington, D. C.

H. Grad
New York University, New York, N.Y.

A three dimensional, scalar-pressure, equilibrium and transport code for systems with closed magnetic field lines is being developed. Of particular interest is a calculation of equilibrium and transport in the EBT device. One of the authors (H.G.) has previously described a method for determining equilibria in general magnetic geometries with closed field lines.[1]

algorithm (formerly called 1½D) similar to ones used previously in two dimensions.[2] The equilibria and magnetic geometry of the problem are three-dimensional, but the transport equations are reduced to one dimension with the volume as the independent variable.

The present method differs significantly from previous equilibrium calculations[4] in that there is no elliptic boundary-value problem to be solved. The magnetic field is calculated from the external coils and the plasma currents which are iterated to self-consistency. The iteration procedure for the equilibrium calculation, which needs to be done only after many transport time steps, consists of two parts. First, the location of the 3D flux surfaces is determined from the surface inductance obtained from integrals along field lines. Next, the value of the flux on these surfaces is calculated by solving an ordinary differential equation, the averaged pressure balance equation. The initial pressure profile is assumed to be given. This method reflects the steady-state nature of EBT in which the conducting walls of the containment device are not in general magnetic surfaces.

In the determination of the 3D geometry, a code developed at Livermore[3] is employed. It calculates magnetic fields from general current distributions and the associated field lines. An important aspect of this code is that it does not employ a filamentary approximation for the currents, but allows for general distributed currents.

* SAI, McLean, Va.

1. H. Grad, Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Vienna, 1971) Vol. III, p. 229.
2. H. Grad, Survey of 1½D Transport Codes, New York Univ. Report COO-3077-154/MF-93 (1978).
3. Sackett, S. J., EFFI - A Code for Calculating the Electromagnetic Field, Force and Inductance in Coil Systems of Arbitrary Geometry, UCRL-52402 (1978).
4. C. L. Hedrick, G. E. Guest, and D. B. Nelson, ORNL/TM-4076 (1973).

1C5

Geometric Optics in Plasmas Characterized by Non-Hermitian Dielectric Tensors

L. Friedland and Ira B. Bernstein

Yale University, New Haven, CT 06520

The theory of geometric optics to date has been limited to plasmas characterized by local dielectric tensors $\underline{\underline{\epsilon}}(\underline{k},\omega;\underline{r},t)$ which are almost hermitian. This restriction was imposed in order to obtain from the dispersion relation $\det \underline{\underline{\epsilon}} = 0$ a real solution $\omega=\Omega(\underline{k};\underline{r},t)$ for real wave vector $\underline{k}$, which is necessary in order to obtain real equations determining the rays of geometric optics, namely $\dot{\underline{r}} = \omega_{\underline{k}}$, along which $\underline{k}$ and the amplitude of the electric field are determined by integrating ordinary differential equations, e.g. $\dot{\underline{k}} = -\omega_{\underline{r}}$ etc. It is shown here that even when $\underline{\underline{\epsilon}}$ is non-hermitian one can generalize the formalism so that nonetheless the new theory is characterized by the same equations determining the rays, and the other equations are unmodified in structure. The theory uses the quasi-dispersion relation $\det\{\underline{\underline{\epsilon}}(\underline{k},\omega+i\nu;\underline{r},t)\cdot[\underline{\underline{\epsilon}}(\underline{k},\omega-i\nu;\underline{r},t)]^{*}\} = 0$ to find complex roots $\omega+i\nu$, where when the approximation of short wave length compared with scale length underlying geometric optics holds, the real part ω serves to generate the rays via $\dot{\underline{r}} = \omega_{\underline{k}}$, and the imaginary part ν enters the transport equation for the amplitude of the electric field.

Work supported by the Department of Energy.

TOROIDAL MODE STRUCTURE OF LOWER HYBRID WAVES

Alan H. Glasser
Auburn University
Auburn, Alabama 36830

The ballooning representation, originally developed to treat low-frequency MHD and kinetic instabilities in a toroidal plasma with magnetic shear, is applied to the toroidal mode structure of linear, cold, electrostatic lower hybrid waves. The results show that as a result of magnetic shear and toroidal periodicity, $k_{||}$ gets large at the cutoff near the plasma edge, and then gets small at the lower hybrid resonance. The magnitude of this effect is sufficient to account for recent experimental results on Alcator A. It also suggests that Landau damping in this intermediate region could have a stronger influence than previously believed.

1C7

POSTER SESSION

MAGNETIC FIELD RECONNECTION IN TOKAMAKS HAVING INTERNAL MAGNETIC SEPARATRICES

M. Rosenberg and F. J. Helton

General Atomic Company
San Diego, California 92138

ABSTRACT

This paper describes a preliminary study of magnetic field line reconnection in tokamaks having internal magnetic separatrices, such as expanded boundary configurations, poloidal divertors, and doublets, drawing upon existing reconnection theories for magnetospheric and solar flare phenomena. We discuss the physical conditions and processes associated with reconnection in physical parameter regimes relevant to laboratory experiments. Then, using Doublet III as an illustration, we discuss possible experimental and numerical consequences of magnetic field line reconnection in the region of the x point. For example, we correlate global changes in the magnetic field topology and the evolution of non-monotone current profiles with time varying external boundary conditions. We point out further studies which could eventually lead to a model for reconnection phenomena in tokamaks with internal magnetic separatrices.

Work supported by Department of Energy, Contract DE-AT03-76ET51011, GA Project No. 3235.

COLLISIONAL LOSSES FROM CONVENTIONAL AND TANDEM MIRROR TRAPS*

P. J. Catto
Science Applications, Inc., Plasma Research Institute, Boulder, Colorado 80302

I. B. Bernstein
Yale University, New Haven, Connecticut 06520

For ions in a tandem mirror or electrons in a conventional mirror, the electrostatic potential Φ is confining. The calculation of the particle loss rate from the electrostatically confined species for a specified Φ was originally performed by Pastukhov[1] by an approximate analytic solution of the Fokker-Planck equation. Subsequent investigations by Cohen et al.[2] have improved and extended Pastukhov's treatment. Pastukhov's technique is rather involved since it relies on detailed knowledge of the distribution function f. We present an alternative description which is variational. It permits a simple trial function approximation to f to be employed to recover an improved analytic expression for the loss rate. In addition, when more general trial functions are employed the integrals can be performed numerically to greatly improve the accuracy. The technique also provides insight into the effect on the loss rate of variation along the field line of Φ and the magnetic field.

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*Work supported by the U. S. Department of Energy under contracts DE-AC03-79-ET-53057 at Science Applications, Inc. and EG-77-S-02-4349 at Yale University.

1. V. P. Pastukhov, Nucl. Fusion 14, 3 (1974).

2. R. H. Cohen, M. E. Rensink, T. A. Cutler, and A. A. Mirin, Nucl. Fusion 18, 1229 (1978).

On the Theory of Internal Disruptions in Tokamaks

H. Welter, D. Biskamp

Max-Planck-Institut fÜr Plasmaphysik
8046 Garching bei München

Internal disruptions are generally believed to be due to the development of the resistive m = 1 kink mode, which grows rapidly without saturation. The time scale τ of this process, which has previously been a matter of speculation is investigated by numerical simulations. For sufficiently small value of the resistivity, one finds $\tau \sim \eta^{-1/2}$, in agreement with the classical reconnection model of Sweet and Parker. In a hot plasma, however, where in addition to resistivity, diamagnetic and viscous effects are important, the nonlinear behaviour may be quite different. For relatively large diamagnetic frequency the m = 1 magnetic island saturates in contrast to the purely resistive case. This may explain some recent experimental observations.

This work was performed under the terms of the agreement on association between Max-Planck-Institut für Plasmaphysik and EURATOM

EVOLUTION OF A LONG COMPACT TORUS

R. N. Byrne and W. Grossmann*
Science Applications, Incorporated
1200 Prospect St., La Jolla CA 92038

The plasma contained within the separatix of a field-reversed theta pinch, such as the FRX experiment(1) at Los Alamos, will lengthen or shorten depending on the balance between field diffusion and energy flow. The general features determining the change in the aspect ratio are contained in a simple model developed by Hamasaki and Linford(2) which holds for very long plasmas, based on the 2D adiabatic calculations of Grossmann and Saltzman(3). We examine these same effects in a finite length plasma(5:1) using the G2M 2D transport code with programmed energy sources and with various impurities added to generate radiation losses. The code follows energy, particle, and flux transport in time, using Grad's technique of iterating between 1D and 2D(4).

As a first step we have chosen initial equilibria (after the implosion or plasma set-up phase of the experiment) which yield relatively long plasma columns but with small plasma pressure on the separatrix. This condition is maintained by rather stringent boundary conditions assumed to hold on the separatrix. FRX data shows, in fact, considerable plasma outside the separatrix and we will describe other boundary conditions similar to those used earlier by Hamasaki(1) which will take the external plasma pressure into account.

We present results of FRX simulations in real time corresponding to the period starting from initial formation to just before strong rotation is observed. We conclude that our model using Braginskii coefficients cannot account for the particle loss observed in FRX. Further studies using the code show, as expected, the plasma column to lengthen dramatically when heat is added rapidly.

(1) R. K. Linford, D. A. Platts, and E. G. Sherwood, Proc. Conf. Plasma Physics and Controlled Nuclear Fusion, IAEA-CN-37/81-1 Innsbruch (1978).

(2) S. Hamasaki and R. K. Linford, BAPS 24, 1081 (1979).

(3) W. Grossmann and J. Saltzman, in proceedings of "2nd Internal Conference on Megagauss Magnetic Field Generation and Related Topics", 29 May - 1 June, 1979, Washington, D.C.

(4) H. Grad, P. N. Hu, D. C. Stevens, Proc. Nat. Acad. Sci. USA 72, 3789 (1975).

*Permanent address: New York University, Courant Institute of Mathematical Sciences.

1C11

BETA LIMITS FOR TORSATRONS

F. Bauer, O. Betancourt and P. Garabedian

The computer code for ideal MHD equilibrium and stability in three dimensions has been upgraded to study ballooning modes of Tokamaks and torsatrons. The Tokamak results agree with linear theories as to critical values of beta and the existence of second stability regions. Moreover, nonlinear saturation is predicted. Because of the distribution of rotational transform, for torsatrons the most dangerous modes turn out to be those with low poloidal and toroidal wave numbers. An $\ell = 2,3$ winding law has been found that leads to beta limits greater than 5% when stabilizing perfect conductors are introduced near the plasma surface. The WISTOR-U experiment proposed at the University of Wisconsin is a configuration similar to the $\ell = 2,3$ torsatron. Beta limits and optimal parameters for that experiment are under investigation by means of a further version of the code that models helical windings outside a vacuum region.

1C12

POSTER SESSION

STABILIZATION OF RESIDUAL KINK MODES IN DOUBLETS AND DEE-SHAPED PLASMAS

L. C. Bernard, F. J. Helton, R. W. Moore, and R. L. Miller

General Atomic Company
San Diego, California 92138

ABSTRACT

Wall stabilization of free surface kink modes may be impractical for tokamak reactors and without wall stabilization, these are potentially the most dangerous MHD modes. Although high β dee-shaped plasmas, stable to all ideal MHD modes, have been found, β is limited in some cases by a "residual" kink mode, whose growth rate is small ($\lambda = - \omega^2/\omega_A^2 \sim 10^{-3}$). We have extended β optimization studies to include doublets, employing the GATO code,[1] which computes the ideal MHD eigenfrequencies and eigenmodes using finite elements to minimize δW. The residual kink mode also appears in doublet equilibria. We have investigated this mode in detail and discuss ways to stabilize it. The impact of these findings on the prognosis for high-beta confinement in noncircular tokamaks will be indicated.

Work supported by Department of Energy, Contract DE-AT03-76ET51011, GA Project Agreement No. 3235.

[1] R. W. Moore, *et al.*, Bul. Am. Phys. Soc. *24*, 1044 (1979).

1C13

Tokamak Transport Calculations for Various Light and Heavy Impurities*

R. A. Hulse and D. E. Post
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

A one-dimensional multi-species impurity transport code has been used to model the behavior of various elements in representative PLT and PDX discharges. Included are loss terms in the edge zones which allow a simple representation of the divertor/limiter region and calculation of the resulting shielding efficiencies.

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1C14

THEORY OF AN ABSOLUTE INSTABILITY OF A FINITE-LENGTH FREE ELECTRON LASER

P. C. Liewer, A. T. Lin, and J. M. Dawson
Physics Department, UCLA

In the free electron laser, coherent electromagnetic radiation is efficiently produced by passing a relativistic electron beam through a static rippled magnetic field. The rippled field (wave number k_o) couples the plasma beam and electromagnetic modes, causing an instability which produces forward-propagating (in the beam direction), short-wavelength electromagnetic radiation at $k \approx 2\gamma^2 k_o$ where $\gamma = (1 - (v_b/c)^2)^{-1/2}$ and v_b is the beam velocity. For moderate beam energies ($\gamma \sim 2$) radiation can be produced whose frequency is suitable for electron cyclotron resonant heating in 40 or 50 kG fields. Thus, the free electron laser could be used like a gyrotron. Unlike the gyrotron, however, the frequency can be tuned by varying the beam energy.

In addition to the short wavelength forward mode, which is convectively unstable, there is also a long wavelength mode ($k \approx -1/2\ k_o$ for $\gamma >>1$) which propagates backward, i.e., the group velocity $v_{em} = d\omega/dk$ is opposite the beam velocity. We find this mode to be absolutely unstable for sufficient system length and/or applied field strength such that

$$\Gamma_o L > \frac{\pi}{2} (|v_{em} v_b|)^{1/2} \qquad (1)$$

provided $v_{em} v_b > 0$ where L is the system length, Γ_o is the infinite system growth rate

$$\Gamma_o^2 = \frac{\omega_c^2}{8} \frac{(k_{em} + k_o)^2}{k_o^2 \quad \gamma^{7/2}} \frac{\omega_p}{\omega_{em}} \qquad (2)$$

where ω_{em} and k_{em} are the frequency and wave number of the backward mode, $\omega_p^2 = 4\pi ne^2/m$ and $\omega_c = eB/mc$ where m is the electron rest mass and B is the strength of the ripple field. Finite-length 1-dimensional particle simulations also show the mode to be unstable provided eqn, 1 is satisfied.

1C15

FREQUENCY SPECTRA AND PARAMETRIC DEPENDENCES OF EBT CORE PLASMA MHD MODES*

D. A. Spong
Oak Ridge National Laboratory, Oak Ridge, Tennessee

Recently the influence of hot electrons on MHD instabilities in EBT has been examined[1,2] using a fully electromagnetic, finite β Vlasov-Maxwell model consisting of 3 species in an inhomogeneous slab geometry with artificial gravity. A similar model is used here, except that finite core electron temperature is allowed and temperature gradients as well as density gradients are included in the core plasma pressure balance. The parametric dependence of the stability boundaries on gradient scale lengths, average radius of curvature, electron-ion temperature ratio, core and ring betas, and hot to core electron density ratio will be presented. Also, the frequency spectra of the modes will be given for parameters typical of the present experiment. These spectra provide a possible point of comparison with experimental measurements of fluctuations which have been made[3] near the T-M transition.

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

[1] D. B. Nelson, "Effect of Hot Electrons on Magnetohydrodynamic Modes in EBT," ORNL/TM-6824 (June, 1979).

[2] J. W. Van Dam, Y. C. Lee, "Stability Analysis of a Hot Electron EBT Plasma," Proceedings of EBT Ring Physics Workshop, Dec. 3-5, 1979, CONF-791228.

[3] M. Fujiwara, A. Komori, private communication.

1C16

EFFECTS OF THE OHKAWA, BOOTSTRAP AND ROTATION CURRENT ON CO-INJECTION β-LIMIT EXPERIMENTS*

J. Hogan

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Significant non-ohmic current densities are predicted to appear in co-injection experiments testing β-limits. We examine a number of these, noting that they should also play an important role in the problem of controlling the current density profile to assure high β in tokamak reactors.

The Ohkawa current, driven by distortion of the background electron distribution, cannot be uniquely identified in ISX-B experiments to date ($P_{inj} \lesssim 1MW$). Significant effects on the current density profile are predicted ($I_{OHKAWA}/I_{OH} \lesssim 0.5$, but $V_{LOOP} > 0$), and it must be included in stability analyses.

The direct contribution of stored fast ions to the current is negligible for densities which yield β above the ideal MHD β limits ($\bar{n}_e > 3.10^{13}\ cm^{-3}$).

The bootstrap current, which should, according to simple estimates, be large in ISX-B experiments ($\beta_{pol}^{ISX-B} \lesssim \sqrt{A}$), is calculated to have a number of non-observed consequences: negative loop voltage, excess of total plasma current over demand value, re-connection (mini-disruption) produced by hollow current density profile, and discrepancy of χ_i^{NC} with the ion power balance by more than an order of magnitude.

The ion rotation contribution cannot be calculated self-consistently without introducing ad hoc damping terms. In the non-damped case, however, ($mn\dot{U}_{\parallel} = K_{beam}$) rotation velocities having a significant effect on the equilibrium are not calculated to build up until after $\beta > \beta_{crit}$.

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Endloss from a High-Beta Plasma Column

by

F. Brunel, T. Tajima, J. N. Leboeuf, and J. M. Dawson

Physics Department
University of California
Los Angeles, California 90024

ABSTRACT

The previous theoretically predicted diverging confinement time of a high-β linear plasma column as $\beta \to 1$ is removed by including the magnetic tension effect near the column throats. This result explains our own simulation as well as those of Brackbill, et. al. and is in good agreement with experimental values. The confinement time τ of a plasma with thickness a and length L at $\beta = 1$ is found to be $\tau = (3/4)\ (3/2\pi)^{1/2}\ (L/2c_s)\ (L/a)^{1/2}$.

1C18

On the Possibility of Achieving Ignition in a High-Field Ohmically Heated Tokamak

C. E. Wagner*

There exists a regime in parameter space where a small high-field ohmically-heated tokamak may be capable of reaching thermonuclear ignition. Results of numerical simulations of the minimum ignition conditions are presented which include empirical, sawtooth, and magnetic field ripple diffusion and the effects of impurities. An ignition condition is derived and compared with the results of the numerical simulations. This criterion states that ignition is possible if the anomalous electron heat conductivity satisfies

$$n\chi_e < (1.8)\ 10^{18}\ (B/A)^2 \left[(1+\kappa^2)/2\right] Z_{eff}{}^{1/6} \Big/ \langle z \rangle^{5/3} \quad .$$

in MKS units where A is the aspect ratio R/a and κ the elongation. Plasma density contraints on ignition are computed and shown to be compatible with the Murakami limit. Achieving ignition in this regime would not require an extrapolation of q_a, ν_*, or β_{max} beyond currently achieved tokamak results.

Work supported by D.O.E.

*Science Applications, Inc.
1200 Prospect Street
La Jolla, California 92038

1C19

EFFECT OF CENTRAL CELL RF ON TANDEM MIRROR CONFINEMENT

T. D. Rognlien and Y. Matsuda
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

We present a theoretical and computational model for the degradation of central-cell ion confinement by an electrostatic ion-cyclotron wave. This study is motivated by the observed degradation of ion confinement in the Livermore Tandem Mirror Experiment (TMX) when plug-driven ion-cyclotron RF fluctuations increase. These fluctuations are also found in the central cell. We model the RF fluctuations in the central cell with a monochromatic electrostatic wave at the plug ion-cyclotron frequency. Central-cell ions that reach the resonant point, where the ion-cyclotron frequency is equal to the wave frequency, are heated by the wave. The heating rate can be calculated by considering the equations of motion near the resonant point, and this rate is in good agreement with numerical single particle orbit calculations. Particle loss is caused by the heating of ions to an energy above that of the potential barrier where angular Coulomb collisions rapidly scatter them into the loss cone. Equating wave and Coulomb heating rates gives an estimate of the electric field level which should affect confinement. Numerical single particle results, including Coulomb collisions by a Monte Carlo method, give a more precise formula for the degradation of the central-cell $n\tau$ as a function of E_{RF}. This result will be compared with TMX experimental data.

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POSTER SESSION

STABILITY OF DOUBLETS TO AXISYMMETRIC RESISTIVE MODES

F. W. McClain

General Atomic Company
San Diego, California 92138

ABSTRACT

We examine the stability of doublets in Doublet III geometry to the resistive axisymmetric MHD modes as formulated by Jensen and Thompson.[1] Stability and growth rates are determined numerically by solving a 2-D eigenvalue equation. The computations imitate accurately the boundary conditions as they exist in the Doublet III experiment.[2] The effects upon stability of the plasma current profile and of the plasma shape (percentage of poloidal flux inside the separatrix, P_s) are considered.

The results of this study are compared to predictions[3] of axisymmetric ideal MHD stability theory for doublets and to experimental observations made in Doublet III. We find that the most unstable resistive mode is one which elongates or contracts the plasma in the vertical direction (droplet-ellipse mode). For a peaked ohmic current profile observed in Doublet III, the code predicts stability only for high percentage flux doublets which is consistent with experimental results.

Work supported by Department of Energy, Contract DE-AT03-76ET51011, GA Project No. 3235.

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

[2] R. W. Callis, "DIII Baseline Design Description," General Atomic Company Report GA-A13996 (1976).

[3] M. S. Chu and R. L. Miller, Phys. Fluids *21*, 817 (1978)

Lower-Hybrid Wave-Driven Currents: MHD Constraints and Antenna Theory*

David A. Ehst and Charles D. Boley
Fusion Power Program
Argonne National Laboratory
Argonne, Illinois 60439

The possibility is investigated that a tokamak reactor could achieve steady-state operation with the toroidal current provided by Landau damping of lower-hybrid waves. According to quasilinear calculations [1], the local power dissipated in driving currents is related to the local current density j by

$$P = \frac{3e^3 \ \ell n \ \Lambda}{5\pi\varepsilon_0^2 m_e c^2} n_e j \frac{\ell n(n_1/n_0)}{n_0^{-2} - n_1^{-2}} ,$$

where the parallel wave vector spectrum is assumed to be peaked within the narrow index of refraction range $n_0 \leq n \leq n_1$. To minimize the rf power needed to sustain the current, it is desirable to attain an equilibrium with a low total current I and with j large at the plasma surface where n_e is low. For a reactor (STARFIRE) with R = 7 m, a = 1.94 m, κ = 1.6, and B_{to} = 5.8 T — currently being designed — we have found such a hollow current profile with I = 10.1 MA, and tested its stability to various ideal and resistive MHD modes. If a conducting wall is present, a toroidal beta of 0.067 can be maintained. A cylindrical equilibrium calculation predicts a minimum required lower-hybrid wave power of 63 MW, at a frequency of 1.4 GHz, with n_0 = 1.20 and n_1 = 1.82. Applying the Brambilla theory of LH wave launching from a phased waveguide array, we have found that wave interference generally produces secondary spectral peaks which do not contribute to current drive. The power loss to these peaks can be reduced by increasing the vacuum distance between the waveguides and the plasma, but this eventually increases the net reflection coefficient. An optimum case with 13 waveguide elements phased by $2\pi/3$, with an appropriate vacuum distance and edge density gradient, has been identified. Details will be presented.

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[1] N. J. Fisch, Phys. Rev. Letters <u>41</u>, 873 (1978); C. F. F. Karney and N. J. Fisch, Phys. Fluids <u>22</u>, 1817 (1979).

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Plasma Heating in a TRACT Reversed-Field Theta Pinch

Loren Steinhauer

Mathematical Sciences Northwest, Inc.
Bellevue, Washington 98009

The Triggered-Reconnnection and Axially-Compressed Torus (TRACT)[1] is a reversed-field theta-pinch formation technique which achieves enhanced heating by means of a two step process: (1) conventional radial shock heating is applied in the presence of a reversed bias field. However, the axial contraction which ordinarily follows immediately after is prevented by means of cusp coils at the end. These coils either prevent reconnection or "grip" the reconnected field lines, preventing axial collapse. (2) After the axial field has risen to its peak value, trigger coils at the ends are fired which induces a strong axial collapse involving strong shock waves. The axial shocks achieve significant additional heating. We have analyzed both the radial and axial shock processes by writing the conservation laws in the form of shock jump conditions. Assuming a particular plasma profile (truncated rigid rotor) the temperature and other plasma properties are thus governed by a set of implicit algebraic equations. We calculate results which predict that temperature enhancements of three to four over straightforward radial shock heating can be achieved by this plasma formation technique.

[1] H.J. Willenberg, A.L. Hoffman, L.C. Steinhauer and P.H. Rose, presented at the U.S.-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, December 12-14, 1979.

CONNECTION RULES FOR THE GENERAL WKB PROBLEM

W. M. Nevins and H. L. Berk
Lawrence Livermore Laboratory, University of California
Livermore, California 94550
and
K. V. Roberts
Culham Laboratories, N. Abingdon, Berkshire, England
and
W. M. Sharp
Naval Research Laboratory, Washington, D.C. 20375

ABSTRACT

We examine the application of phase integral methods to the solution of equations of the form

$$\Gamma(i \frac{\partial}{\partial x}, x) \phi(x) = 0 \qquad (1)$$

where Γ is a differential operator of finite or infinite order. Eq. (1) has asymptotic "wave" solutions in regions of the complex x-plane delimited by Stokes lines satisfying $\mathrm{Re}\int_{x_{ij}}^{x} [k_i(x) - k_j(x)] dx = 0$, where x_{ij} is a turning point in the complex x-plane where the branches $k_i(x)$ and $k_j(x)$ coalesce.

We have established a set of rules similar to Furry's for continuing wave solutions across Stokes lines. A major complication in the theory is that with a differential operator of 3rd (or greater) order the Stokes line from turning point x_{ij} may cross a Stokes line from $x_{jk}(i \neq k)$. When such a crossing occurs a naive application of Furry's rules gives non-unique results.

We resolve this difficulty by representing the solutions as path integrals in the complex k-plane. Furry's rules may then be obtained by studying the changes in the topology of the steepest descent paths in the complex k-plane as x is varied. With this representation a unique result is obtained when continuing an asymptotic solution past a pair of crossed Stokes lines. We show that the correct continuation of the solution may be obtained without reference to the k-space representation of the solution provided that Stokes line crossings are appropriately re-ordered.

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

POSTER SESSION

1C24

Helical Plasma Equilibria*

M. S. Chu, C. Chu, F. W. McClain, M. Schaffer, T. Ohkawa*

General Atomic Company
San Diego, California 92138

ABSTRACT

The equilibrium of a straight, helically symmetric, current-carrying plasma is investigated numerically. The plasma is limited either by a material limiter or the separatrix. At low current, the configuration resembles an ohmically heated stellarator. At high current, a high-shear configuration with pitch reversal[1] was obtained with appropriate parameters. The pitch reversal could be achieved from either the helical effect or the paramagnetic effects alone or from a combination of both. Local interchange stability calculations show that the high shear make the configuration (not fully optimized) stable for $\beta \sim 15\%$.

*Work supported by General Atomic Company.

[1] T. Ohkawa et al., GA-A15561.

1C25

SIMULATION OF THE FORMATION PHASE OF SPHEROMAK*

Y. Li and D.D. Schnack

National Magnetic Fusion Energy Computer Center
Lawrence Livermore Laboratory
Livermore, California

We are using a nonlinear, two-dimensional, resistive MHD code to simulate the formation phase of the Spheromak plasma. The full MHD equations are solved throught the domain. The core, which carries both toroidal and poloidal source currents, is modeled as a highly viscous, highly resistive region. Fluid flow and current are thus excluded from its interior, and the problem of specifying self-consistent boundary conditions on its surface is avoided. The current sources are simulated by dividing the magnetic field into plasma and vacuum contributions. Preliminary results are presented.

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

Simulation of Low Frequency Doublet Heating

Michael E. Kress and Harold Grad

Courant Institute of Mathematical Sciences
New York University

We continue to evaluate low frequency (~60 Hz) heating of Doublets by oscillating motion of the separatrix which induces (inductively) a very sharp current peak localized near the moving separatrix. A very efficient and accurate Alternating Dimension code[1] is used to simulate linear and nonlinear plasma behavior. Previous results[2] are extended in accuracy and in scaling of parameters: to smaller amplitude (linear, improved signal/noise) to correspond to present experiments in Doublet III; to more adiabatic parameters to more closely correspond to a reactor regime; to more than one pair of oscillating driving coils to simultaneously achieve a no-skin boundary condition and constant total plasma current; and to investigate the number of oscillating F-coils required to approximate a no-skin pointwise boundary condition.

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

[1] H. Grad, P. N. Hu, D. C. Stevens, in Sixth IAEA Conference, Berchtesgaden, (1976)

[2] H. Grad, T. H. Jensen, M. E. Kress, Bull. APS, 24, 976 (1979)

Poster Preferred

Please do not schedule on Wed., Apr. 23.

1C27

ASPECTS OF DRIFT WAVE TURBULENCE IN TOKAMAKS*

P. H. Diamond and M. N. Rosenbluth
The Institute for Advanced Study, Princeton, New Jersey 08540

ABSTRACT

A theory of collisionless electrostatic drift wave turbulence in tokamaks is presented. The electron drift kinetic equation is renormalized using the procedure of Dupree and Tetreault.[1] The renormalized equation contains a representation of the $(c/B_o^2)(\hat{E}_\perp \times B_o)\cdot\nabla f$ nonlinearity which contains portions proportional to Φ and f and which includes non-Markovian effects. The renormalization is shown to satisfy constraints necessary for consistency with conservation of energy.

Using an approximation technique which greatly simplifies the complicated spectrum sums which must be dealt with; the renormalized drift kinetic equation is solved to obtain an analytic approximation to the nonlinear electron response which in turn is used to construct the eigenmode equation. The nonlinear stability problem is analyzed in two regimes. For $\omega_c < \omega$ $(\omega_c^3 = k^2 v_T^2 D_{k,\omega}/3L_s^2)$ the turbulence is found to have a *stabilizing* affect, and the rate of decrease of total *mode spectrum* energy is calculated. A similar conclusion is reached by a more accurate analysis of the resonance broadening calculation. For $\omega_o > \omega$, substantial quantitative but *not* qualitative modifications to the theory of Hirshman and Molvig[2] are found. In particular, a lower saturation amplitude is predicted, but the basic picture of turbulent destabilization competing against linear and nonlinear shear damping remains.

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*This work was supported by the United States Department of Energy Contract No. DE-AC02-76ET, 53011,A003.

[1] T.H. Dupree and D. J. Tetreault, Phys. Fluids 21, 425 (1978).

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

1C28

BALLISTIC PROPAGATION OF INTENSE ION BEAMS

William B. Thompson

Department of Physics, University of California, San Diego

ABSTRACT

This paper explores the possibility of delivering power densities of order 10^{14} watts/cm^2 to feasible pellets at a 5-10 meter stand off distance by means of ballistically focussed beams of light ions.

Range of the pellet limits energies to $\sim$ 1 MeV/A, and scattering cross sections limit the background pressure to $\sim 10^{-5}$ torr, while the beam must satisfy stringent emittance requirements and be neutralized by cold electrons.

Routes avoiding instabilities, or schemes in which the effects of unavoidable instabilities are inoffensive will be described as will the stringent requirements on the source.

Nonlinear Evolution of Ballooning Modes*

W. Park, D. A. Monticello, R. B. White,
H. R. Strauss[†], and S. C. Jardin
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

Nonlinear evolution of ballooning modes in a high β tokamak is studied using a three-dimensional dynamic code HIB. It is found that the ballooning unstable plasma evolves into a saturated 3-D state which possesses singular current sheets. This singular behavior is analogous to the nonlinear saturation mechanism of internal kink modes.[1] A method utilizing an artificial field[1] is employed to numerically resolve the singularity in the current profile.

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*Work supported by U. S. DoE Contract DE-AC02-76-CH03073.

[†] Permanent address: Courant Institute, New York University, New York.

1. W. Park, D. A. Monticello, R. B. White, and S. C. Jardin PPPL-1635 (1980).

1C30

LOW FREQUENCY TRAPPED-ELECTRON TEARING INSTABILITY*

R. Marchand
Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20740

A new, low frequency electromagnetic eigenmode is found to be unstable when corrections to the electron response are introduced, to account for trapped particles in a tokamak. The model assumes flute like perturbations and the governing eigenmode equations are solved using a slab model. For simplicity, temperature gradients and collisions are neglected and attention is focused on the tearing parity only (even $A_{\parallel}$ and odd ϕ). The interest of this mode comes from the fact that, in the slab model and for realistic parameters, it is the only instability which exists in the collisionless limit. The numerical results presented indicate that the mode frequency scales roughly as the fraction of trapped particles, $\sqrt{\varepsilon}$, and that the growth rate is only mildly affected by β. The influence of the equilibrium electron current and of a small electron collision frequency is also discussed.

*Supported by Office of Naval Research.

Launching of Lower-Hybrid Waves in Self-Consistent Density Profiles*

Ernest Valeo
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

Calculations by Brambilla[1] have accurately predicted the experimentally observed[2] dependence of plasma reflectivity on parameters such as density scale length and waveguide dimensions and phasing for incident fluxes below several hundred watts/cm^2. Recent experimental data at higher power levels[3] suggests that nonlinearities cause important deviations from the linear coupling theory. We have extended Brambilla's grill calculation to include plasma response to the ponderomotive potential. Launching and propagation in the resulting self-consistent density profiles are under study.

[1] M. Brambilla, Nucl. Fusion 16, 47 (1976)

[2] S. Bernabei, M. A. Heald, W. M. Hook, R. W. Motley, F. J. Paoloni, M. Brambilla, and W. D. Getty, Nucl. Fusion 17, 929 (1977)

[3] R. W. Motley, W. M. Hooke, and C. R. Gwimm, Princeton Plasma Physics Laboratory Report PPPL-1642, (March, 1980)

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* Work supported by U.S. DoE Contract #DE-AC02-76-CH03073.

Effect of Finite Toroidal Mode Number on Ballooning Stability in Multipoles

E. A. Adler, University of California, Los Angeles
Y. C. Lee, University of Maryland

In recent MHD studies of ballooning modes in multipoles,[1,2] the critical pressure gradient was determined by looking at the stability boundary for modes with infinite azimuthal mode number. It is well known that, since finite Larmour radius effects limit the maximum mode number, this calculation gives an underestimate of the actual critical β. Asymptotic analysis can be used to show that the correction to βcrit is $0\ (m^{-1})$ and that the width, in flux space, of the least stable displacement is $0(m^{-1/2})$. We have used perturbation theory to obtain a one dimensional eigenvalue equation for the amplitude of the displacement as a function of flux. We have solved this equation numerically for linear multipoles. We will discuss our results and their implications for current multipole experiments.

[1] D. A. D'Ippolito, E. A. Adler, and Y. C. Lee, Phys. Fluids 23 (1980).
[2] M. W. Phillips, Bull. APS 24 (1979).

The Integral Method in Linear Plasma Theory.

G. KNORR, Dept. of Phys. & Astron., Univ. of Iowa,
Iowa City, IA 52242.

The solution of the linearized Vlasov equation in the electrostatic approximation can be written as

$$f_1(\underline{r},\underline{v},t) = - \frac{q}{m} \int_0^t \nabla'\varphi(\underline{r}',t') \frac{\partial}{\partial \underline{v}} f_o \, dt' \qquad (1)$$

where the time integral follows particle trajectories. f_o is usually constructed from constants of the motion. For inhomogeneous plasma problems, the usual procedure is to make an ansatz $\exp(i\omega t)$ with the complex eigenvalue ω and perform the time integral. Then f_1 is integrated over velocities. Assuming quasi-neutrality, viz. putting

$$n_{1,e} = n_{1,i} \quad , \qquad (2)$$

expanding in a Taylor series in the direction of the inhomogeneity, one obtains a differential equation, which has to be solved for the complex eigenvalue ω. The procedure has by now become quite complicated and in order to obtain reliable results, one uses numerical shooting methods [1] to determine ω and thus information on stability and instability.

We propose here a different approach: We integrate Eq. (1) over velocities, but keep the time dependence. Together with Eq. (2) this results in a Volterra equation of the first kind. For homogeneous plasmas it takes the simple form

$$\int_0^t \varphi(t')K(t - t')dt' = H(t) \quad .$$

It is of interest that the large difference in masses, which is often difficult to handle numerically, turns out to be helpful in this representation. By integrating over a few oscillations (practically not more than two), one obtains the desired results, $\mathrm{Re}(\omega)$ and $\mathrm{Im}(\omega)$. In order to obtain the accuracy of the method, a Lorentz profile was used for $f_o(v)$, which allows closed analytic calculation of $\mathrm{Im}(\omega)$ for ion waves. The relative error of $\mathrm{Im}(\omega)$ was 5.10^{-2} for 50 mesh points per period, 5.10^{-4} for 200 mesh points, and 3.10^{-5} for 400 mesh points, using a second order integration scheme. The method becomes useful for inhomogeneous problems, because then realistic boundary conditions, e.g., $\varphi(x = 0) = \varphi(x = L) = 0$ can easily be incorporated.

This work was in part supported by U.S. Department of Energy Grant EY-76-S-02-2059.

[1] K. T. Tsang, P. F. Catto, F. C. Whitson, and F. Smith, Phys. Rev. Lett. 40, 327 (1978).

1C34

Ballooning Mode Stability in Linear Multipoles*

Darrell A. Skinner, Department of Physics, University of Wisconsin--An analytic condition has been derived which is necessary for stability to ballooning modes in the short wavelength limit ($k \to \infty$). The system under consideration is a linear multipole with *n* hoops equally spaced about a circle. The result is a transcendental equation, which except near the separatrix has a simple approximate form

$$\frac{dP}{d\psi} \lesssim \tilde{P}_{\psi} \left(1 + \frac{\langle D\rangle_b}{\langle D\rangle_g}\right) \qquad \textit{necessary for stability}$$

where $D \equiv \dfrac{1}{BR_{\text{curvature}}}$

$$\langle\ \rangle_{g,b} \equiv \int \frac{d\ell}{B} \qquad \textit{over good or bad curvature portions of closed fieldline}$$

$$\tilde{P}_{\psi} = n^2\pi^2 \, \frac{\langle D^2/B^2\rangle_b}{\langle D\rangle_b^3}$$

$\tilde{P}_{\psi}$ corresponds to the critical pressure gradient in this theory for a mode whose perpendicular displacement ξ_{ψ} is completely localized in the bad curvature region. But the most unstable mode is not necessarily well localized there, especially not near ψ_{crit} (where $\langle D\rangle_b + \langle D\rangle_g = 0$). The above result shows that for stability, $dP/d\psi \to 0$ as $\psi \to \psi_{\text{crit}}$.

The method consists in constructing a trial function $\vec{\xi}$ which satisfies only certain properties of the exact marginally stable eigenfunction, namely, zero compressibility, localization near a flux surface, and a relation for ξ_{χ} in terms of ξ_{ψ}. But ξ_{ψ} itself is determined from an analytically soluble approximation to the exact eigenvalue equation for $dP/d\psi$ and ξ_{ψ}. The energy principle is used with this trial function to demonstrate a necessary condition.

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*Work supported by the University of Wisconsin Graduate School.

1C35

Penetration of Lower Hybrid Waves for Heating in Tandem Mirrors

K. A. Connor and J. T. Woo
Plasma Dynamics Laboratory
Rensselaer Polytechnic Institute
Troy, New York 12181

D. B. Batchelor and R. C. Goldfinger
Fusion Energy Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 34383

R.F. heating of $T_{i\perp}$ and $T_{e\parallel}$ in the end plugs of tandem mirrors is of interest for improving the tandem mirror concept. Waves at the lower hybrid range of frequencies are well suited for such applications because the ion and electron absorption mechanisms are of the desired form. A matter of concern to the application of LHRF waves is the penetration of the wave energy. This question is investigated for model tandem mirror parameters by applying ray tracing techniques. Ray trajectories are determined using the Appleton-Hartree dispersion relation while absorption by electron Landau damping is calculated locally for a finite temperature plasma. The windows in parameter space for realizing specific forms of heating are identified.

1C36

SINGLE-MODE SATURATION IN MIRROR MACHINES*

R.C. Myer and Albert Simon
University of Rochester
Rochester, NY 14627

We have used an analytic model of single-mode saturation in mirror machines for comparison with the PR-6 experimental data.[1] If one uses the ion temperature (150 ev) stated in Ref. 1, it is very difficult to fit either the linear or nonlinear observations. A much improved fit is obtained if one uses a considerably higher ion temperature (400 ev) at the onset of instability. A recent paper by Kanaev[2] acknowledges that cold ions were streaming in during the early stages and delayed onset of the instability.

Using this higher temperature, we obtain much improved agreement with the observed linear frequency and wavelength, and with the magnitude of the unstable electrostatic oscillations. There is a fit to the magnitude and variation of the floating potential, but the predicted decrease of the ion density in the unstable regime is considerably smaller than observed.

In the model discussed above, ion loss was represented by an electron-drag-like term. An improved model, with ion mirror-loss gives promise of a more complete match to the observations.

*Research supported by U.S. Department of Energy under contract DE-AS02-76ET53032.

[1] B.I. Kanaev and E.E. Yushmanov, Sov. Phys. JETP 40, 290 (1975).
[2] B.I. Kanaev, Nuclear Fusion 19, 347 (1979).

1C37

MTT--Modular Torus with Twisted Toroidal Field Coils*

K. E. Weimer and J. L. Johnson†
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

A modular stellarator configuration can be produced by properly deformed toroidal field coils.[1] Elimination of the helical conductors solves a basic difficulty in the construction of a conventional stellarator reactor. K. Ohasa and K. Miyamoto[2] developed an analytic theory for a straight warped-coil system ($Z \sim d_w \sin \ell \theta$). They evaluated the rotational transform at the magnetic axis where only the fundamental mode is important and obtained a moderate transform. We have extended this work by introducing an additional twist[3] ($Z \sim d_w \sin \ell\theta + d_t \sin 2 \ell \theta$). Numerical calculations confirm that reasonably large transforms can be achieved. As the radius is increased, higher modes cause ι to gradually flatten and even to decrease near the outer surface.

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

†On loan from Westinghouse R & D Center.

1. S. Rehker and H. Wobig, Max-Planck Institut für Plasmaphysik Report IPP 2/215, 1973.
2. K. Ohasa and K. Miyamoto, Jap. J. Applied Phys. 16, 813, (1977).
3. T. K. Chu, H. P. Furth, and C. Ludescher, Bull. Am. Phys. Soc., 24, 956, (1979).

POSTER SESSION

POSTER SESSION

1C38

EXPANDED BOUNDARY APPROACH*

N. Ohyabu

General Atomic Company
San Diego, California, U.S.A.

ABSTRACT

The impurity problem associated with high heat flux, the ash removal question, and disruption control are major concerns for tokamak reactors. A new edge cooling scheme, the expanded boundary approach, has been proposed to solve these problems. In this concept, the outermost flux surfaces are expanded in order to provide a large volume for radiative cooling. Two methods are suggested to achieve the desired configuration. One is to deform the poloidal configuration; the other is to use an external helical field to destroy the outer flux surfaces.

Due to various transport effects specific to this configuration, both the impurity density and the electron density are increased in the boundary region. This makes it possible to employ the most desirable form of heat removal, i.e., to convert the heat flux from the core plasma into radiative power without an accompanying deterioration of energy confinement.

The approach can also accomplish the other important functions carried out by more traditional divertors, namely the shielding of the impurity flux and the pumping of the alpha particle ash. If this concept is combined with an elaborate poloidal coil system, it may be possible to minimize the number of major disruptions.

The basic concept and its planned implementation on Doublet III will be discussed together with possible applications in an upgraded version of Doublet III. Some information will also be offered on the compatibility of this approach with reactor engineering requirements.

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

Self-Similar Formulation of 1-D Plasma Flow*

H. Hsuan and G. Elder

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

Self-similar techniques(1) have been found useful in solving ideal fluid equations in the case of point blast explosions(2) and thermal conduction studies.(3) One-dimensional plasma flow including electron thermal conduction as well as convection can be formulated in terms of self-similar variables. Equations for continuity, momentum and energy transport are used along with assumptions of quasi-neutrality and negligible electron-ion energy transfer. Self-similar solutions are not totally determined by the set of equations. We find that the physics of the problem, represented by proper "conservation laws", removes the final degree of freedom in the mathematical formulation. For example, in the case of conservation of mass, momentum, or energy, the self-similar variable is found to be x/t; while a constant heat flux at the boundary yields X/t^A where $A = 2(\phi + 1)/(2\phi + 1)$ and the coefficient of electron thermal conductivity is assumed to be proportional to T^{ϕ}. This formalism may be useful in studying theta pinches(4) and divertor flow.

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

(1) G. W. Bluman, J. D. Cole "Similarity Methods for Differential Equations" Springer-Verlag New York, Inc., New York (1974).

(2) e.g. G. B. Whitham "Linear and Nonlinear Waves", John Wiley and Sons, New York p. 191 (1974).

(3) Ya. B. Zel'dovich and Yu. P. Raizer, "Physics of Shock Waves Hydrodynamic Phenomena" (Edited by W.D. Hayes and R.F. Probstein) Vol II, Academic Press, New York and London (1967).

(4) R.L. Morse, Phys. Fluids 16, 545 (1973).

1C40

PARTICLE SIMULATIONS OF MAGNETIC X-POINTS: TOPOLOGY CHANGE AND PLASMA HEATING

J. N. Leboeuf, T. Tajima, J. M. Dawson and E. Canobbio
Department of Physics, UCLA

Fully self-consistent particle simulations of magnetic X-points are carried out and compared with the conventional MHD X-point pictures. The simulation is based on two-and-one-half dimensional magnetostatic (high β cases) and electromagnetic (low β cases) particle codes with external currents. For a 1-to-1 system size or magnetic X-point scale lengths ratio, the X-point configuration is stable. For a 2-to-1 system size and high β, changes in topology include displacement of the X-point along the axis, formation of an island at the center, incessant attachment and detachment of the island from the O-point. For low β, the topology changes from an X-point to a neutral sheet plus two Y-points and finally to an X-point at the center upon appearance of vacuum with flow into the O-point where the plasma is confined. Irrespective of stability of the X-point, the mass flow is greatly influenced by the electrostatic fields and the current flow by finite Larmor radius effects. Results of X-point heating by ringing the X-point (poloidal) fields at characteristic ion frequencies in presence of a toroidal field will also be reported.

This work was supported by DOE and NSF.

1C41

CALCULATION OF VELOCITY SPACE DIFFUSION FOR A CHIRIKOV-TAYLOR MODEL*

A. B. Rechester

Plasma Fusion Center
Massachusetts Institute of Technology, Cambridge, MA., 02139

R. B. White

Plasma Physics Laboratory
Princeton University, Princeton, N. J. 08540

We have developed an analytical method to calculate the diffusion coefficient for charged particles moving in a field of electrostatic waves. We applied our theory to a Chirikov Taylor model.

$$x(t + 1) = x(t) + v(t)$$

$$v(t + 1) = v(t) + \varepsilon \sin(x(t+1))$$

Here x is a coordinate, v is a velocity and time t takes an integeger values t = 0,1,2,... The expression obtained for the diffusion coefficient in the region $\varepsilon >> 1$ is

$$D = .5\varepsilon^2[.5-J_2(\varepsilon)\exp(-\sigma)-J_1^2\ (\varepsilon)\exp(-\sigma)+J_3^2(\varepsilon)\exp(-3\sigma)]$$

$J_n(\varepsilon)$ are Bessel functions. Parameter ε is proportional to electric field amplitude and σ is related to additional random processes, for example numerical errors. The diffusion coefficient predicted by the theory agrees well with numerical computations.

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ORAL PRESENTATION

1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

THIRD-ORDER ELECTROMAGENTIC WAVE INTERACTIONS IN A PLASMA*

W. B. Riesenfeld
Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico 87545

We examine the detailed structure of the nonlinear, third-order interaction of electromagnetic waves in a magnetic field-free plasma. The particular process considered is the Raman-Induced Kerr Effect (RIKE)[1] in which two incident waves, a circularly polarized pump wave propagating obliquely with respect to a linearly polarized probe wave, interact with each other and an electrostatic plasma wave to produce an elliptically polarized final wave propagating in the probe direction. The process is of third order in the sense that the fluctuating plasma current responsible for radiating the final wave is cubic in the incident field amplitudes. When certain resonance conditions are fulfilled this scattering process turns out to be coherent, yielding a final wave of sufficient amplitude to be of experimental and diagnostic interest, despite the high order of the interaction. Resonance occurs when the incident wave frequencies, both lying well above the plasma frequency, differ by the latter. The third-order calculation is carried out on the basis of a simple plasma model which displays all the expected resonance and coherence features. A motivation of this work is an analogous study for the case of a magnetoplasma, in which an extraordinary wave is excited in place of the electrostatic plasma wave and resonance occurs at the upper hybrid frequency. It is conjectured that such a scattering process can yield a useful new diagnostic tool for measuring local magnetic fields in high-beta plasmas[2,3,4].

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

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2. R. W. Hellwarth, Appl. Phys. 11, 147 (1976).
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4. P. R. Forman and W. B. Riesenfeld, Los Alamos Report LA-8262-MS, March 1980.

1C43

1980 SHERWOOD THEORY MEETING

Tucson, Arizona - April 23-25, 1980

STARTUP OF THE REVERSED-FIELD PINCH IN A QUASI-ADIABATIC MODE*

E. J. Caramana
Los Alamos Scientific laboratory
Los Alamos, New Mexico 87545

It is essential that a Reversed-Field Pinch discharge be initiated such that a diffuse low-beta plasma result at the end of the formation phase. A diffusive startup, where the positive toroidal bias field is present before the main toroidal current is initiated, can never fulfill this requirement without substantial losses since the plasma heating that results from current diffusion across the initial toroidal field leads to a high beta.[1] We consider a method of forming a Reversed-Field Pinch on a slow timescale, through a series of equilibrium states that involves more adiabatic compression than diffusion. We solve the purely adiabatic formation problem by transforming the cylindrically symmetric MHD equations into a poloidal flux representation where the explicit time dependence of the formation problem can be solved analytically. Atomic physics processes and resisitive MHD activity may cause substantial departure from the ideal model. The manner in which these effects may be calculated by means of a one-dimensional transport code is discussed. Certain differences and similiarities between Reversed-Field Pinch and tokamak startup are mentioned.

*This work performed under the auspices of the U. S. Department of Energy.

1. D. A. Baker and J. A. Phillips, Phys. Rev. Letters 32, 202 (1974).

1C44

Taylor Relaxation in a Torus of Arbitrary Cross-Section and Aspect Ratio*

A. Reiman
Laboratory of Plasma Studies, Cornell University
Ithaca, New York 14853

In a self-reversed z-pinch, the induced wall current must be greater than the current carried by the external field coils. The contribution of these wall currents to the energy was neglected by Taylor in his work on the relaxation of a z-pinch plasma.[1,2] We redo Taylor's analysis including the neglected term. We also generalize the analysis to arbitrary cross-section and aspect ratio. Although the energy due to wall currents can be large, and must be included in the analysis, we show that this contribution never alters the minimum energy state.

For the spheromak configuration, the equilibria of interest have no surface current. Nevertheless, to determine the stability of these equilibria we must compare their energy to that of other force-free equilibria which do have surface currents.

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

[1] J. B. Taylor in Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, 1975), Vol. I, p. 161.

[2] A. Reiman, Phys. Fluids 23, 230 (1980).

SHERWOOD THEORY MEETING
Tucson Arizona April 23-26

1C45

Ion cyclotron wave propagation in a hot toroidal plasma for R.F.Heating

Michel COTSAFTIS

ASSOCIATION EURATOM-CEA SUR LA FUSION
Département de Recherches sur la Fusion Contrôlée
Centre d'Etudes Nucléaires
Boîte Postale n°6, 92260 FONTENAY-AUX-ROSES (FRANCE)

ABSTRACT :

The wave propagation equation in the ion cyclotron range is obtained for hot toroidal plasmas with multiple ion species and arbitrary cross-sections from the Vlassov + Maxwell set of equations.

To the first significant orders in the finite Larmor radius (FLR) and the small $\beta = B_{pol}/ B_{tor}$ parameter expansion, ie 2nd order for FLR and 1rst order for β , the global wave structure including self consistently the (Landau and cyclotron Landau) absorption, is described by a single 4th order 2-D Partial Differential Equation (E) which is given in geometric form. To lowest order, this equation reduces to a 2nd order Helmoltz type 2-D equation (E_o) which shows a "singularity" near the ion-ion hybrid layer where the wave structure is strongly affected because the wave vector becomes very large. The effects of the 3rd order β term and the 4th order FLR terms in (E) to remove the singularity of (E_o) are discussed, and it is mainly shown that, when now proporly including the difference between the flux surfaces and the wave are not likely to dominate nor even occur in most of the situation.
So, the wave propagation and absorption is adequately represented by (E_o) only, and the main role of the singularity is to allow by the induced change of the wave vector along the magnetic field, Landau absorption for the electrons and cyclotron Landau absorption for the ions in a domain in betweem the ion-ion hybrid layer and the cyclotron layer, and heating of the species in proportions depending of the parameters.
This is in agreement with observations and seems to be highly interesting for future large size experiments.

ORAL Presentation Preferred

1C46

Microinstabilities in Tokamaks as an Initial Value Problem[*]

C.Z. Cheng

Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

and

C.O. Beasley, Jr., K.T. Tsang, and D.J. Sigmar

Oak Ridge National Laboratory
Oak Ridge, TN 07830

and

J. Denavit

Northwestern University
Evanston, IL 60201

An initial value approach is presented to study essentially any microinstabilities with $k_{||}/k_\perp \ll 1$, $\omega/\omega_{ci} \ll 1$ in tokamaks without making approximations such as small gyroradius, inverse aspect ratio, or magnetic drift expansions. This approach permits (1) to incorporate Fokker-Planck collision terms easily, (2) to obtain information about either absolute or convective modes, and (3) to include nonlinear terms. These advantages are either difficult or impossible to achieve by using eigenvalue analysis. In tokamaks the curvature and magnitude of the magnetic field is not uniform over a magnetic surface. This nonuniformity can cause coupling among different poloidal harmonics. The linearized drift/gyro kinetic equations, describing microinstabilities in axisymmetric tokamak, are intrinsically two dimensional in $(\psi,\theta,v_{||},v_\perp)$ phase space. Employing high n ballooning mode formalism, the linearized equations are reduced, in lowest order in $1/n$, to 1½-dimensional equations in $(\eta,v_{||},v_\perp)$ phase space where η is the coordinate along the magnetic field line. This results in a great savings in computation. Numerical results will be presented for the ion temperature gradient (η_i) modes. Ion magnetic drift terms are found to have a strong destabilizing effect and contribute to a small negative frequency shift. Detailed results over a wide range of parameters will also be presented.

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

1C47

TIME EVOLUTION OF UNSTABLE ALPHA PARTICLE DISTRIBUTION IN TOKAMAK[*]

D. J. Sigmar, W. I. van Rij and K. Molvig[+]
Oak Ridge National Laboratory, Oak Ridge, Tennessee

Depending on the rapidity of heating to ignition, a spherically symmetric but hollow α-distribution f_α will arise,[1] in spite of the smoothing effect of α-electron collisions. Taking into account the ripple and other spatial losses of the alphas, an unstable α-distribution can be maintained. The instability considered is at $\omega \sim \ell\, \omega_{c\alpha} \simeq c_A k_\perp$ where c_A is the Alfven velocity and $4 \leq \ell \leq 10$, with $k_\perp \rho_\alpha \gtrsim 1$, and $\omega_{c\alpha} = \omega_{c\alpha}^o (1 + \varepsilon \cos \theta)$ as described previously.[2] Because of the double periodicity of the gyromotion in tokamak geometry quasilinear theory is applicable even for this relatively narrow spectrum of unstable cyclotron harmonics. A numerical solution of the quasilinear diffusion of f_α is obtained, coupled with the ion heat balance equation in order to investigate anomalous ion heating.

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[*] Research sponsored by the Office of Fusion Energy (ETM), U. S. Department of Energy under contract W7405-eng-26 with the Union Carbide Corporation.

[+] Massachusetts Institute of Technology, Cambridge, MA.

[1] D. Mikkelson, J. Cordey, R. Goldston, private communication, and D. J. Sigmar in Proceedings of Workshop on Plasma Near Thermonuclear Condition, Varenna, 1979.

[2] K. Molvig, D. J. Sigmar, 1978 Sherwood Conference.

2A1

Self-Constant Potential Variations in Thermal Barriers*

by Jay Kesner

Department of Nuclear Engineering
University of Wisconsin
Madison, Wisconsin 53706

and

Georg Knorr and D. R. Nicholson
Department of Physics and Astronomy
The University of Iowa
Iowa City, Iowa 52242

Self-consistent electrostatic potential variations are considered for several model situations which share important features with proposed tandem mirror thermal barriers (which do not contain sloshing ions). For some conditions, equivalent to a prescribed pre-acceleration, the desired potential depressions are found. The electron to ion temperature is seen to play a critical role in determining the necessary pre-acceleration. When these parameters are not properly adjusted no steady-state negative potential solutions are found.

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*Work supported by U.S. D.O.E. and by NSF Atmospheric Research Section.

2A2

FOKKER-PLANCK STUDIES OF THE INTERACTION BETWEEN TRAPPED AND UNTRAPPED ELECTRONS IN MAGNETIC MIRRORS*

A.A. Mirin

National Magnetic Fusion Energy Computer Center
Lawrence Livermore Laboratory
Livermore, California

I.B. Bernstein, R.H. Cohen, and M.E. Rensink

Lawrence Livermore Laboratory
Livermore, California

The effect of passing electrons on the confinement of electrons trapped in a magnetic mirror with confining electrostatic potential is examined. A two-dimensional, nonlinear Fokker-Planck code is used to compute the trapped electron distribution for a given distribution of passing electrons. Approximate analytic solutions of the linearized Fokker-Planck equation are also given. These yield expressions for the particle and energy exchange rates, which are asymptotically valid for large $\Delta\phi/T$ and either large or small mirror ratio. Generally good agreement between the theory and code results is found. An important result is that under a wide range of conditions, the confining potential $\Delta\phi$ between the plug and the barrier of a thermal-barrier tandem mirror machine is given by a modification of the Maxwell-Boltzmann result, namely,

$$e\Delta\phi = T_{ep}\ell n\left[(n_p/n_b)\ (T_{ec}/T_{ep})^{1/2}\right]$$

Applications to TMX and MFTF-B will be given.

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

Poster session preferred.
Place in a different session from M.E. Rensink and A.A. Mirin, "Some Factors Influencing The Radial Structure of Tandem Mirror Plasmas"

2A3

Electrostatic Drift-Ballooning Mode Turbulence in Tokamaks*

S. P. Hirshman, P. H. Diamond,[+] M. N. Rosenbluth,[+]
L. Chen,[++] K. Molvig,[+++] J. C. Whitson and J. Smith

Oak Ridge National Laboratory
Oak Ridge, TN 37830

Analytic and computational investigations of electrostatic drift-ballooning mode turbulence in plateau regime tokamak plasmas are presented. A renormalized electron drift-kinetic equation which is consistent with energy conservation is derived and solved in the ballooning mode representation to yield the non-linear electron response to a turbulent spectrum of toroidally unstable ballooning modes. An integro-differential eigenmode equation is obtained from quasineutrality using a linear ion response which incorporates toroidal effects. For turbulent decorrelation frequencies $\omega_c > \omega$, the eigenvalue problem is solved using a variational procedure, yielding approximate saturation criteria. Trial functions are used corresponding to both toroidicity induced (TI) branches, which are due to local bound states, as well as toroidally modified slab-like (TS) eigenmodes. For the linearly unstable TI modes, the saturation amplitude is determined by a balance of turbulently reduced electron growth and nonlinearly induced shear damping. At saturation, the turbulent modification of the local potential well due to toroidal coupling allows finite mode energy to flow toward the region where it is ion Landau damped. Perturbation theory for small $\omega_c < \omega$ indicates an accelerated non-linear growth rate for the TI modes, thus suggesting the accessibility of the saturated state. For the TS modes, saturation arises from toroidally enhanced shear damping, leading to a diffusion coefficient which is reduced from its slab value by finite $\varepsilon = r/R$ corrections.

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[+] The Institute for Advanced Study, Princeton, NJ 08540

[++] Plasma Physics Laboratory, Princeton University, Princeton, NJ 08540

[+++] Plasma Fusion Center, MIT, Cambridge, MA 02139

Variational Principle for Low Frequency Stability of Collisionless Plasmas*

T.M. Antonsen Jr., B. Lane, and J.J. Ramos

Massachusetts Institute of Technology
Cambridge, MA 02139

We examine the stability of an arbitrary β collisionless plasma to modes with wavelengths greater than the ion gyroradius. The stability of such a plasma to perturbations that grow on the hydrodynamic time scale is determined by the kinetic energy principle[1,2]. A configuration which is predicted to be stable on the basis of the kinetic energy principle may still be unstable to modes that grow with a frequency comparable to the diamagnetic or curvature drift frequency. We derive a new kinetic energy principle that gives sufficient conditions for instability of these low frequency modes. The energy principle indicates that two types of instabilities are possible; the first corresponds to the low frequency electrostatic, trapped particle mode, and the second is the low frequency limit of MHD (interchange and ballooning) modes. The kinetic modifications to the interchange (Mercier) criterion are evaluated and the effect of the kinetic terms on ballooning modes is estimated.

For a tokamak with $\beta \sim \varepsilon$, where ε is the inverse aspect ratio, the new kinetic terms scale as $\varepsilon^{1/2}$ whereas the old kinetic terms[1,2] scale as $\varepsilon^{3/2}$ (3).

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1) M.D. Kruskal and C.R. Oberman, Phys. Fluids 1, 275 (1978).

2) M.N. Rosenbluth and N. Rostoker, Phys. Fluids 2, 23 (1959).

3) P. Rutherford and L. Chen, unpublished.

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

2A5

DYNAMICAL DETERMINATION OF OHMIC STATES OF A CYLINDRICAL PINCH*

D.D. Schnack

National Magnetic Fusion Energy Computer Center
Lawrence Livermore Laboratory
Livermore, California

Among the fundamental questions concerning the Reversed Field Pinch is the mechanism for generation and maintenance of the reversed axial field. One possible mechanism for the attainment of this state is the nonlinear evolution of an m = 1 resistive kink instability. We use a nonlinear, two dimensional resistive MHD code to determine that, if the initial state is paramagnetic enough, a reversed axial field can be attained in this manner by mode activity of a single helicity. More significantly, we show that the final helical, reversed field configuration which results can be maintained against resistive diffusion by dynamo action. Such reversed field states represent steady, non-stationary equilibria in which force balance and Ohm's law are self-consistently satisfied, and are called Ohmic states.

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

1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

FINITE BETA REVERSED-FIELD PINCHES AND INCOMPLETE RELAXATION*

Leaf Turner
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545
J. P. Christiansen
UKAEA/Euratom, Culham Laboratory, Abingdon, Oxfordshire
OX14 3DB, United Kingdom

A preliminary study of plasma confinement in a Reversed-Field Pinch (RFP) configuration is made. Because the outer region of an RFP discharge has higher resistivity and lower temperature than the inner region, we idealize experimental RFP configurations by choosing a plasma model in which the wall values of the current density and pressure are zero. A homogeneous, isotropic resistivity is assumed. The Bessel functions provide a complete basis for representing a cylindrically symmetric current density: $j_\theta(r) = \sum_n \lambda_n a_n J_1(\lambda_n r)$ and $j_z(r) = \sum_n \gamma_n b_n J_o(\gamma_n r)$; with $J_1(\lambda_n r_o) = 0$ and $J_o(\gamma_n r_o) = 0$ for all n, and where r_o = wall radius. Associated with each harmonic is a wavelength and time scale for resistive diffusion.

In a steady state, we envisage unspecified turbulent processes occurring on Kolmogorov-like length and time scales, ℓ_N and τ_N, respectively. We suggest that these processes may culminate in an "α-effect"[1] that opposes resistive diffusion of spectral modes with $n \lesssim N$. The α-effect is then calculable without the customary recourse to kinematic assumptions if one invokes a principle of incomplete relaxation of the plasma: in the absence of electric fields the resistive plasma relaxes to a state of minimum magnetic energy compatible with the constraints of constant magnetic helicity K and magnetic flux Φ, as well as with the resistive truncation of the spectrum at $n \simeq N$. Thus K and Φ determine the a_n's and b_n' for n = 1,2,...N. The extent of relaxation is governed solely by the value of ℓ_N.

The values of β_θ,F, and Θ obtained with the incomplete relaxation model are consistent with experimental data. However, our results for the pressure profiles are sensitive to the details of the resistive truncation. Elucidation of this profile sensitivity is vital for a truly credible model of plasma relaxation.

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

1. E. N. Parker, Astrophys. J., 122, 293 (1955).

2A7

Fast Alfven Wave ICRF Heating and Its Effect on Single Particle Confinement in Tokamaks Including Coulomb Collisions*

K. W. Whang and G. J. Morales
Physics Deparment
University of California, Los Angeles

Fast Alfven wave heating of minority ions and the associated thermalization with the majority ion and electron populations through Coulomb collisions is considered in tokamak geometry. A set of finite difference equations which connect the magnetic moment, parallel velocity and phase between successive resonances are derived under the assumption that the RF kick produces a nonadiabatic jump in the magnetic moment at the resonance layer. A continuous slow-down model is used to describe the parallel motion together with a Monte-Carlo method which takes care of the pitch angle scattering. Questions concerning the effect of the collision-induced stochasticity on the heating, the determination of the threshold wave electric field amplitude, and the heating rate are considered and the answers are compared with the collisionless results. The effect of collisions on the enhanced ion loss due to the enlargement of the banana orbits produced by cyclotron resonance heating is also discussed.

*Work supported by DOE and ONR.

2B1

NUMERICAL STUDY OF LOW TOROIDAL MODE NUMBER INSTABILITY IN A COMPACT TORUS

A.I. Shestakov, D.D. Schnack, and J. Killeen

National Magnetic Fusion Energy Computer Center
Lawrence Livermore Laboratory
Livermore, California

We use the computer program RIPPLE VI [1] to investigate the stability of a numerically generated 2-D equilibrium [2] closely modeling the Field Reversed Theta Pinch. The instabilities are assumed to vary as $f_1(r,z,t)\exp(in\phi)$ $n\neq 0)$. Results are presented for n = 1,2,3 and for a spectrum of magnetic Reynolds number, S, $(=10^2 - 10^4)$. We find the equilibrium to be unstable for all three mode numbers; the growth rates and mode structure to be independent of S. The modes are somewhat more localized and the growth rates decrease slightly with increasing n.

[1] J. Killeen, D.D. Schnack, and A.I. Shestakov, Proc. of 4th IRIA Intl. Symp. of Computing Methods in Applied Sciences and Engineering, Versailles, France, Dec. 10-14, 1979, also Lawrence Livermore Laboratory Report UCRL-83332.

[2] D.V. Anderson and T.A. Cutler, Proc. of 8th Conference on Numerical Simulation of Plasmas, Monterey, Calif., June 28-30, 1978.

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

2B2

ION-CYCLOTRON HEATING OF A VLASOV-FLUID THETA-PINCH PLASMA COLUMN*

R. Sanchez and F.L. Ribe
University of Washington

ABSTRACT

The Vlasov-Fluid model[1,2] with warm electrons, extended to account for anisotropy of the ion equilibrium distribution, is applied to the description of small, linear oscillations of a theta-pinch plasma for a range of wave frequencies covering ion-Landau damping as well as ion-cyclotron resonant effects, i.e., the wave Doppler-shifted frequency $\lesssim$ ion gyrofrequency. To lowest order in a finite-Larmor-radius expansion, an MHD-like equation of motion is derived. This equation contains resonant terms originating from ion-Landau damping and from ion-cyclotron resonant effects. When the wave frequency is of the order of the (ion gyroradius/plasma radius) x ion gyrofrequency, this equation reduces to the one obtained in a previous work[3] using a different ordering. Appropriate boundary conditions are also discussed, and a closed-form solution for a sharp-profile plasma is given.

References:

1. J.P. Freidberg and L.D. Pearlstein, Phys. Fluids 21, 1201 (1978).
2. T.E. Cayton and H.R. Lewis, to be published.
3. R. Sanchez, submitted for publication to Phys. Fluids.

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

2B3

SHORT WAVELENGTH COLLISIONLESS TEARING MODES*

R. G. Kleva
Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20742

Recently, Tsang, Whitson, and Smith[1] presented a numerical analysis of the coupled set of eigenmode equations (Ampere's law and the quasineutrality condition) which describe electromagnetic perturbations in a sheared slab magnetic field. In particular, they found a damping rate for tearing-like perturbations (even $\tilde{A}_{\parallel}$, odd $\tilde{\phi}$) which deviated somewhat from the analytic prediction $\gamma = k_y \Delta' v_e / 2\pi^{1/2} k_o^2 \ell_s)$,[2] where $\Delta' = -2k_y$ is the jump in the logarithmic derivative of $\tilde{A}_{\parallel}$ across the singular layer, and $k_o \equiv d^{-1}$ where $d \equiv c/\omega_{pe}$ is the collisionless skin depth. Using the technique of Antonsen,[3] we obtain a dispersion relation which is in good agreement with these numerical results. This dispersion relation is not restricted to modes which satisfy the constant -$\tilde{A}_{\parallel}$ approximation. For modes with wavelength λ satisfying $\rho_e < \lambda < d$ the dispersion relation predicts a damping rate $\gamma \sim -v_e/\ell_s$ which is smaller than previously predicted.

*Supported by Office of Naval Research.

[1] K. T. Tsang, J. C. Whitson, and Julius Smith, Phys. Fluids 22, 1687 (1979).

[2] J. F. Drake and Y. C. Lee, Phys. Fluids 20, 1341 (1977).

[3] T. M. Antonsen, Phys. Rev. Lett. 41, 33 (1978).

1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

OHMIC HEATING STUDIES OF THE REVERSED FIELD PINCH*

Richard Gerwin and R. W. Moses, Jr.
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 98545
R. A. Nebel
University of Illinois
Urbana, Illinois 61801

An analytic model and a self-consistent one-dimensional heating and transport code (RFPBRN)[1] are applied to the ohmically heated Reversed Field Pinch (RFP). Ignition conditions and conditions for unignited power amplifiers are elucidated by parameter studies. For example, the minimal ignition condition for the RFP may be simply characterized as a curve of the current-line density ratio, (I/N), versus temperature. Along this curve the hypothesized thermal conduction loss rate is increasing relative to bremsstrahlung. If this loss rate is too large, ignition for reasonable I/N values and reasonable temperatures may be unobtainable by ohmic heating alone; nevertheless under such conditions thermonuclear power amplifiers of modest currents and dimensions with $\beta \sim 10\%$ appear to be possible. In these calculations the analytic model has been found to agree reasonably well with this and other transport codes to which it can furnish interpretation and guidance. Quantitative differences between model and codes are readily explained through profile considerations.

*This work was performed under the auspices of the U.S. Department of Energy.

1. R. A. Nebel, R. L. Hagenson, R. W. Moses, and R. A. Krakowski, Los Alamos Scientific Laboratory Report LA-8185-MS (January 1980).

2B5

NUMERICAL MODELING OF ELECTRON DIFFUSION DUE TO DISTURBED FLUX SURFACES

M.G. McCoy and A.A. Mirin
National Magnetic Fusion Energy Computer Center
Lawrence Livermore Laboratory
Livermore, California
and
R.W. Harvey
General Atomic Company
San Diego, California

A 2-D program to simulate electron heat loss due to disturbed flux surfaces in tokamaks is under development. The program combines a velocity and radially dependent heat source H(v,r), and a 1-D Fokker-Planck treatment of the electron collisions $C(f_e)$ with a loss operator which simulates diffusion on paths in velocity-radius, described by

$$\frac{\partial f_e}{\partial t} = H + C(f_e) + \frac{1}{rv} \mathcal{L} v^3 r D \mathcal{L}(f_e),$$

where $\mathcal{L} = (\frac{\partial}{\partial r} - \frac{eE(r)}{m_e v} \frac{\partial}{\partial v})$, E(r) is the radial ambipolar electric field, and D is a diffusion coefficient.$^{(1)}$ Previously, the loss operator was calculated assuming that the electron distribution was locally maxwellian.$^{(2)}$ However, the resulting electron tail distributions contravene the assumptions inherent in the linearization of the loss term. It is hoped that this model which calculates the loss term non-perturbatively will eventually allow credible estimates of the consequences of electron transport due to disturbed flux surfaces. Some preliminary results are presented.

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

[1] Kim Molvig, John E. Rice, and Miloslav Tekula, Phys. Rev. Lett., Vol. 41, No. 18, 1240, (1978).

[2] R.W. Harvey, K.D. Marx, and M.G. McCoy, UCRL-83667, (1980).

Poster session preferred.

2B6

Plasma Edge Boundary Conditions
for 3D Plasma Transport

Harold Grad

Courant Institute of Mathematical Sciences
New York University

The Alternating Dimension ($1\frac{1}{2}$D) method for macroscopic transport has been generalized to arbitrary 3D toroidal plasma systems.* The principal results are:

1. derivation of evolution equations for $\partial\psi/\partial t$ and $\partial\chi/\partial t$: with explicit second derivatives (diffusion) and geometrical coefficients;

2. explicit calculation of (three) eigenvalues of the second derivative matrix, representing relative diffusion in 1D among the four adiabatic variables (mass, entropy, two fluxes). For example, diffusion of one flux relative to the other (skin effect) has the coefficient $D = \eta(\psi')^2(\Lambda_{11}\Lambda_{22} - \Lambda_{12}^2)$, where Λ_{ij} is the inverse surface inductance matrix.

Now we supplement these equations with boundary conditions and study of singular behavior at the plasma edge ($\rho = p = 0$):

1. at a limiter or divertor;

2. at a free boundary vacuum interface.

For example, at a limiter, $T \to 0$ (logarithmically), and at a free boundary, $T \sim (\bar{\psi} - \psi)^{-\alpha} \to \infty$ $(0 < \alpha < 1)$.

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

* H. Grad, Proc. of IRIA Conference, Versailles, Dec. 1979

Please do not schedule on Wed., Apr. 23

POSTER SESSION

ENHANCED SINGLE-PARTICLE CONFINEMENT IN THE ELMO BUMPY TORUS CONCEPT

R. A. Dandl,* D. Dobrott, G. Guest and W. Bard

General Atomic Company
San Diego, California 92138

ABSTRACT

In a bumpy torus of infinite aspect ratio, the single-particle guiding centers move on concentric, bumpy cylindrical surfaces with circular cross sections. As the aspect ratio, R/a, is reduced, these nested surfaces become distorted in shape and shifted relative to each other. For sufficiently small aspect ratio, they may no longer close inside the vacuum chamber, particularly for particles which are barely trapped by the magnetic mirrors. The shape distortion and degree of relative shift in the centers of the drift surfaces can be minimized by modifications to the magnetic coils making up the torus. Here we discuss comparative studies of wedge coils and aspect ratio enhancement coils which illustrate two of the proposed techniques for optimizing the confinement of single particles. Various criteria for judging the effectiveness of the modified configurations will be discussed, together with the related role of current density in the coils.

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*Consultant

2B8

1980 SHERWOOD THEORY MEETING
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STABLE STARTUP AND BURN SIMULATIONS FOR A REVERSED FIELD PINCH*

R. A. Nebel and G. H. Miley
University of Illinois
Urbana, Illinois 61801

R. W. Moses
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

Using RFPBRN,[1] a one-dimensional Lagrangian mesh transport and stability code, a scenario has been found that theoretically maintains ideal MHD stability to global and local modes through both the startup and burn phases of a Reversed-Field Pinch (RFP) reactor. Startup is achieved using pitch programming,[2] which is modeled in the code as a large compression. To insure stability, results indicate it is necessary to peak the toroidal current off axis in the prereversed state as well as maintain a minimum-free pitch profile.[3] The implications of this on the RFP reactor and future work are discussed.

*This work was performed under the auspices of the U.S. Department of Energy contracts EY-76-S-02-2218 and W-7405-ENG-36.

1. R. A. Nebel, R. L. Hagenson, R. W. Moses, and R. A. Krakowski, "Comparison of Zero-Dimensional and One-Dimensional Thermonuclear Burn Computations for the Reversed-Field Pinch Reactor (RFPR)", Los Alamos Scientific Laboratory report LA-8185-MS (Jan, 1980).
2. A. A. Newton, "Pitch convection", HBTXII Workshop, Culham Laboratory, U.K., (1974).
3. D. C. Robinson, "High-β Diffuse Pinch Configurations", Plasma Phys. 13, 434-462 (1971).

Plasma Potential Modification and Cold Ion Stoppering Due to Ponderomotive Effects on Electrons*

R. A. Jong, W. J. Fader and E. A. Sziklas

United Technologies Research Center
East Hartford, CT 06108

The application of moderate power rf near the local ion cyclotron frequency in the mirror region of a mirror confined plasma has shown evidence of cold ion stoppering resulting from the rf. We present a model which can explain the cold ion stoppering produced by axial electric fields in the range of 20-50 V/cm. Field strengths of this magnitude do not significantly affect the ions directly but are shown to have a large influence on the electron confinement. The model shows that the rf produces a ponderomotive force which enhances electron confinement and thus alters the ambipolar potential and improves the cold ion confinement. We will discuss the range of validity of this model and the scaling to large mirror systems.

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2B10

Model of a Plasma Hitting Neutral Gas*

A.H. Boozer and R.A. Jacobsen

Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

The mechanical feasibility of tokamak divertors would be greatly enhanced if the outflowing plasma could be stopped by a neutral gas in the divertor chamber rather than on a neutralizer plate. The viability of this operating mode hinges on whether the neutral density in the divertor chamber can be large enough to have a significant effect and still allow a low neutral density around the main plasma. Due to the subtlety of the boundary conditions, we studied the simple but informative one dimensional problem

$$\frac{dP}{dx} = -\nu_x \Gamma \ , \quad \frac{dq}{dx} = -\nu_E P \quad \text{with} \quad P = \Gamma^2/\rho + \rho T/m$$

the total or dynamic pressure. The mass flux Γ and energy flux q are assumed given at $x = 0$ with Γ independent of position. The momentum of the flow is lost through charge exchange at a rate ν_x and energy is lost at a rate characterized by ν_E. The heat flux q is assumed to be dominated by electron parallel thermal conductivity and vanishes when the temperature drops to T_R, the recombination temperature. The problem is not determinate until one assumes that the pressure at $x = 0$ is as low as it can be consistent with physical constraints. The physical constraint which limits the input pressure is that the density be real at the recombination point. The distance the plasma penetrates the neutral gas is found to be $L = C_H/(\nu_x \nu_E)^{\frac{1}{2}}$ with $C_H = [2q(x = 0)/\Gamma]^{\frac{1}{2}}$. The temperature at $x = 0$ is given by $q(x = 0) = -(6/7)K(T_o)T_o/L$ with K the parallel electron conductivity. The flow velocity at $x = 0$ is $(\nu_o/\nu_x)^{\frac{1}{2}}(T_o/m)/C_H$ while the Mach number at the recombination point is one.

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Oral preferred.

2B11

MAGNETIC FLUX DIFFUSION IN A TOKAMAK REACTOR*

Y-K. M. Peng, J. A. Holmes and K. E. Rothe
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

In the operation of a tokamak fusion reactor it may be necessary, for MHD stability reasons, to control the pulse duration. In an ETF (engineering test facility) this is expected to be hundreds of seconds, which is comparable to the resistive time scale which governs the evolution of the q-profile. We study the evolution of the q-profile on the resistive time scale numerically using a 1 1/2 dimensional single fluid transport code.[1] This code couples one dimensional energy balance, particle balance, and magnetic flux diffusion equations to a two dimensional axisymmetric MHD equilibrium equation through the pressure p, poloidal flux function ψ, and safety factor q. The diffusion and conduction coefficients include annomalous electron and neoclassical ion contributions consistent with experimental observations[2,3] plus a contribution which models the effect of magnetic ripple diffusion. The classical Spitzer resistivity is used. Source terms include particle fueling, neutral injection, ohmic heating, and nuclear alpha heating.

We consider the evolution of a realistic q-profile for two high beta ($\beta_T \sim 6\% - 16\%$) cases: 1) a beam driven hydrogen plasma having no nuclear alpha heating, 2) an ignited D-T plasma in which the neutral injection has been turned off. A Monte Carlo neutral beam calculation is used to obtain the deposition profile, which can be varied by changing the neutral beam energy and/or the plasma density. For the beam driven plasma it is shown that hollow beam heating profiles lead to steady state q-profiles in the time scale of interest, while centralized heating profiles lead to decreasing q values at the plasma center over the relevent times. We further show that the centralized nuclear heating in an ignited D-T plasma causes the evolution of the q-profile for this case to behave much like that in the centralized heating beam driven case: namely, the q values near the plasma center decrease over the time scales of interest. The flux diffusion process may set a limit to the plasma burn time in ETF.

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

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[3] H. Eubank, et al., "PLT Neutral Beam Heating Results," in Plasma Physics and Controlled Nuclear Fusion Research, (Proc. 7th Int. Conf. Innsbruck, 1978) Vol. 1, IAEA, Vienna (1979) 11.

2B12

POSTER SESSION

RELAXATION OF NEUTRAL BEAMS IN THE PRESENCE OF HIGH FREQUENCY INSTABILITIES

D. K. Bhadra, S. C. Chiu and R. W. Harvey

General Atomic Company
San Diego, California 92138

ABSTRACT

The perpendicular injection of energetic neutrals into a tokamak plasma is expected to create a highly anisotropic ion velocity distribution which is susceptible to various instabilities. Instabilities at the lower hybrid frequency, and/or at the nearby ion cyclotron harmonics have been observed in cylindrical plasma devices, such instabilities being characterized by waves that are resonant with the perpendicular velocity of the beam. For near-perpendicular injection into the Doublet III device, excitation of such waves is possible. We consider the dynamics of such oscillations in a tokamak geometry. When the characteristic growth time is shorter than the collisional relaxation time, wave-particle interactions can be expected to modify the energy transfer process; in general, diffusion in velocity space of both plasma and beam particles may result, giving possibly a decrease in beam-slowing down time. Whether or not this causes an enhanced loss of particles depends on the scale of the resulting micro turbulence.

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Heating by Collisional Slowing of Fast Ions in Non-Circular Tokamaks§

L. M. Hively, J. Rome*, and G. H. Miley
Fusion Studies Laboratory
Nuclear Engineering Program
University of Illinois
Urbana, Illinois 61801

The fast ion collisional slowing-down problem has been formulated to describe large banana-width guiding-center orbits in an axisymmetric, non-circular tokamak. Orbits are labeled by the ion speed, v, the maximum poloidal flux function along the guiding center orbit, ψ_X (ψ increases from the magnetic axis), and the cosine of the angle between the parallel component of plasma current and the ion velocity evaluated at ψ_X, $\zeta = \vec{J}_{\parallel} \cdot \vec{v}/|\vec{J}_{\parallel} \cdot \vec{v}|$.

The Fokker-Planck equation is bounce-averaged after the variables have been transformed to the COM space. Neglecting pitch-angle scattering, speed-diffusion, and charge-exchange, the Fokker-Planck equation can be reduced to a first-order, 3-D partial differential equation. It is solved using the method of characteristics, giving μ/E as a constant of the motion (μ = magnetic moment and E = ion energy). The resulting particle distribution function is $f = \tilde{S}/(4\pi v^2\ dv/dt)$, where $\tilde{S}$ is the bounce-averaged alpha source rate and dv/dt is the bounce-averaged slowing rate along the slowing-down characteristic.

Moments of the distribution function yield the alpha particle density, current, and heating profiles. There is a net co-going alpha current due solely to finite banana-width effects. Results show that central ion heating by the alphas is 10-15% below in-situ deposition, indicating that start-up and maintenance of ion temperature may be more difficult than anticipated. However, the lower central alpha density (in comparison to in-situ) indicates a reduced alpha ash accumulation on-axis, somewhat relaxing the impurity removal problem.

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§Work supported by the Department of Energy.

*Address: Oak Ridge National Laboratory, Oak Ridge, TN.

2B14

POSTER SESSION

VARIATIONAL THEORY OF ELECTRICAL CONDUCTIVITY AND KINETIC TEARING MODES

C. S. Chang, R. R. Dominguez, and R. D. Hazeltine*

General Atomic Company
San Diego, California 92138

ABSTRACT

A variational theory for Ohm's law, valid for arbitrary collision frequency, is presented for a slab geometry using a pitch-angle scattering collision operator. Shear and temperature-gradient effects are included but toroidicity is neglected. The variational conductivity is used to examine the effects of shear and electron temperature gradients on tearing mode instabilities. We show that shear has a strong stabilizing effect on the so-called "collisional" and "semi-collisional" electron temperature-gradient tearing-mode instabilities. In addition, we discuss the stabilizing effect of shear on the classical resistive and inertial tearing modes.

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*Present address: University of Texas, Austin, TX.

Abstract submitted to 1980 Sherwood Theory Meeting, Tucson, Apr. 23-25, 1980

TWO-DIMENSIONAL SIMULATION OF THE FORMATION OF THE PPPL SPHEROMAK[1]

H. C. Lui, C. K. Chu, and A. Aydemir[2]

Plasma Physics Laboratory

Columbia University

Various schemes proposed for the creation of the spheromak in the PPPL experiment are simulated by our two-dimensional, time-dependent, compressible, resistive MHD code.[3] In these schemes, the toroidal fields and poloidal currents in the plasma are induced by a solenoidal discharge in a core, while a toroidal coil inside the core produces the major part of the initial poloidal fields, as well as the main toroidal plasma current. Various programming schemes for the current in the toroidal coil, including current reversal, control the toroidal plasma current and poloidal field profiles. Poloidal field reconnection, toroidal field compression, and plasma accumulation into a spheromak geometry are achieved in the various schemes with or without the aid of pinching coils.

Our results substantiate the results of Jardin's incompressible code calculations [4], and show additionally regions of concentrated plasma density and vacuum. For several schemes, using proper programming of currents, realistic parameter values give effective spheromak formation.

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1) Work supported by USDOE under contract EY-76-S-02-2456 and in part by PPPL.

2) Now at Los Alamos Scientific Laboratory.

3) See, e.g., H.C. Lui and C.K. Chu, Phys. Fluids 18, 1277 (1975). Also, A. Aydemir, C.K. Chu, H.C. Lui, Proc. US-Japan Symp on Compact Tori, PPPL Dec. 1979, p. 176.

4) S. Jardin, Proc. US-Japan Symp. on Compact Tori, PPPL Dec.1979, p.166. Also paper submitted to present meeting.

2B16

INFLUENCE OF CROSS-FIELD DIFFUSION ON THE STABILITY OF THE COLLISIONAL DRIFT WAVE*

C. L. Chang, J. F. Drake, A. B. Hassam, and C. S. Liu
Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20742

The linear stability of the collisional drift wave in a sheared magnetic field is reexamined allowing for cross-field particle and thermal diffusion. The sixth order set of equations, obtained from Braginskii's fluid equations, is solved numerically. It is found that the mode is stable regardless of the relative strength of the perpendicular diffusion. This result demonstrates that simple cross-field diffusion may not necessarily destabilize the drift wave. In particular, it suggests that the recent investigation[1] which concluded that cross-field diffusion destabilizes the universal mode should be more carefully examined.

*Supported by U.S. Department of Energy.

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

2B17

SIMULATIONS OF THE FORMATION AND EVOLUTION OF THE PS-1 SPHEROMAK*

A. G. Sgro† and D. Winske
University of Maryland
College Park, Maryland 20742

C. K. Chu and H. C. Lui
Columbia University
New York, New York 10082

We present results of numerical modeling of the formation and evolution of the University of Maryland Paramagnetic Spheromak PS-1. Since the preformation length of the plasma is 3 times the radius, one dimensional (r only) simulations are used to describe the conditions near the midplane (in z) during the formation phase, i.e., for one to two bounce times ($\lesssim 2\ \mu s$). The longer time evolution is being studied in two dimensions.

The one dimensional simulations have indicated the following: heavy ion impurities, emitted from the electrodes, are present in the preformation plasma and affect the implosion dynamics; a low density current carrying plasma between the spheromak plasma and the wall is present and affects the toroidal field distribution; the magnetic field penetration is anomalously fast, the anomalous resistivity being approximately the same function of plasma parameters as that resistivity which successfully described the evolution of the sheared fields in the ZTS reversed field pinch; a fraction $f \gtrsim 0.5$ of the anomalous joule heating is deposited directly into the ions, as predicted by microturbulence theory.

Two dimensional simulations are being used to study reconnection (given the resistivity inferred from the ID simulations), the initial equilibrium and its evolution with time. Preliminary results will be presented.

*Supported by U.S. Department of Energy.
†Permanent Address: Los Alamos Scientific Laboratory, Los Alamos, NM 87545.

2B18

Extended Time Behavior of an Unstable or Damped Single Mode*

Thierry Dewandre and Albert Simon
University of Rochester
Rochester, NY 14627

The O'Neil-Morales[1,2] analysis correctly predicts the nonlinear time behavior of Landau damping (or the growth of a weak bump-on-tail instability) for time of order τ, where τ is the trapping time. We are extending the analysis to longer times, in order to determine the ultimate behavior. For times of order $t \cong \omega_p \tau^2$, the nonresonant electrons begin to contribute to the nonlinear behavior and can have a major effect. It is also necessary to carefully study very early time (linear) phase-mixing in order to properly subtract large terms in the study of the long-time integrated amplitude change.

[1] T.M. O'Neil, Phys. Fluids 8, 2255 (1965).

[2] G.J. Morales and T.M. O'Neil, Phys Rev. Lett. 28, 417 (1972).

*Research supported by U.S. Department of Energy under contract DE-AS02-76ET53032.

2B19

NONLINEAR EVOLUTION OF RIPPLING MODES IN CYLINDRICAL GEOMETRY*

H. R. Hicks, P. W. Gaffney, B. Carreras†, D. K. Lee, V. E. Lynch
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

A finite-resistivity plasma should exhibit not only low mode number tearing modes, but high mode number rippling modes driven by the gradient of the resistivity.[1] A nonlinear three dimensional initial value calculation has been performed using reduced resistive MHD equations with an electron heat conduction equation.[2] In this equation there are two competing forces; a convective term which creates nonconstant resistivity on flux surfaces, and a finite parallel heat conduction term (with coefficient $K_{||}$). At low $K_{||}$ all resonant modes are unstable, with both tearing-dominated and rippling-dominated modes present. The dependence of linear growth rate on toroidal and poloidal mode number, on the level of resistivity and on $K_{||}$ is investigated. Numerical considerations for high mode number and high $K_{||}$ calculations are discussed.

A Δ' analysis is performed for low $K_{||}$. The results compare excellently with the initial value code results. The linear eigenfunctions show a definite transition from $\Delta' > 0$ at low mode number to $\Delta' < 0$ at high mode number.

The nonlinear stabilization of single-helicity rippling modes is investigated. The study of rippling modes with resonant surfaces very close to each other shows that they exhibit a nonlinear coupling.

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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.

†Present address: Institute for Advanced Study, Princeton, New Jersey 08540

[1] H. P. Furth, J. Killeen, M. N. Rosenbluth, Physics of Fluids 6, 459 (1963).

[2] B. Carreras, H. R. Hicks, J A. Holmes, B-V. Waddell, ORNL/TM-7161, February 1980.

Interchange Stability of Plasma Confined by Field-Reversed Ion Rings*

A. Mankofsky, L. Sparks, R. N. Sudan
Laboratory of Plasma Studies, Cornell University
Ithaca, New York 14853
and
J. Denavit
Department of Mechanical Engineering, Northwestern University
Evanston, Illinois 60201

We have performed numerical studies of the interchange stability of a warm plasma confined on closed field lines generated by field-reversed ion rings. Equilibria are generated by the RINGA code,[1] with plasma pressure taken into account by (i) including an $r\ dp/d\psi$ term in the equation for the vector potential A_θ, and (ii) including fast ion-electron drag in the particle equations of motion. The interchange stability condition, derived from the energy principle,[2] is then evaluated on each flux surface using a high-order transformation code.

We present results which demonstrate how stability is affected by the plasma β (i.e., the hollowness of the radial current profile at a given axial position) and by the pressure cutoff (i.e., whether plasma exists on or beyond the separatrix). Preliminary findings indicate that the outermost flux surfaces are always unstable, while the innermost surfaces seem to be marginally stable or just barely stable, at best. Finite pressure on the separatrix may be stabilizing.

We also present a status report on the development of a hybrid RINGA, which includes electron dynamics. The thermal electron fluid included in this new code will allow, among other things, the study of the above problem in a fully self-consistent fashion.

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

[1] A. Mankofsky, A. Friedman, R. N. Sudan, J. Denavit, 8th Conf. on Numerical Simulation of Plasmas (Monterey, CA, 1978), paper #PE-4.

[2] J. L. Johnson, R. M. Kulsrud, K. E. Weimer, Plasma Physics <u>11</u>, 463 (1969).

2B21

Rippling Modes in the Edge of a Tokamak Plasma?*

J.D. Callen and M.E. Benchikh-Lehocine
University of Wisconsin, Madison, WI 53706

The edge of a tokamak plasma is very turbulent.[1] In contrast to the situation in the hot plasma center, the edge is also rather collisional. Namely, for $T_e \lesssim 100$ eV and $n_e \sim 10^{13}$ cm^{-3} the collisional mean free path becomes shorter than the connection length ($2\pi Rq$) and the plasma is in the Pfirsch-Schlüter regime. In this collisional regime a gradient in the electrical conductivity along the magnetic field lines can exist and hence rippling modes[2] can occur. The rippling modes seem to have slightly larger growth rates and radial extent than the other possible resistive MHD modes in this collisional regime -- the "resistive-g" modes.[2] The possibilities for occurrence and characteristics of these modes in the edge of a tokamak plasma and their potential for anomalous transport will be discussed.

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

[1] S.J. Zweben, C.R. Menyuk, and R.J. Taylor, Phys. Rev. Letters 42, 1270 (1979).

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

2B22

ION CYCLOTRON RESONANCE HEATING
IN A TANDEM MIRROR*

James E. Howard and Jay Kesner
University of Wisconsin
Madison, Wisconsin 53706

Our previous work on single particle estimates of $\Delta v_\perp$ for fast and slow waves in a parabolic well is expanded and used to calculate midplane and off-midplane heating rates. An estimate of inadvertant heating of central cell ions is also carried out. The various effects of the Doppler shift on resonance width, overlap, and virtual resonances are investigated and used to estimate superadiabaticity limits in Phaedrus.

* Work supported by U.S. Department of Energy contract No. ET-79-S-02-5125.

Monte Carlo Simulation of Helium Ash Enrichment in a Proposed ETF/INTOR Divertor*

D. Heifetz, D. E. Post, and M. Petravic
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

A Monte Carlo calculation of Seki, Shirmomura, and Maki [1] is re-done with a more complete set of reactions and various geometries and results are compared.

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2B24

TEARING MODE STABILITY OF A LONG-THIN REVERSED-FIELD THETA PINCH*

J.M. Sayer and D.D. Schnack

National Magnetic Fusion Energy Computer Center
Lawrence Livermore Laboratory
Livermore, California

and

H.L. Berk

Lawrence Livermore Laboratory
Livermore, California

An investigation of tearing mode instabilities for reversed field cylindrical plasmas without toroidal field is presented. Stability criteria are developed using the method of neighboring equilibria. Three dimensional effects are included by means of the long-thin approximation. Analytical and numerical examples show that stability is enhanced as flux is excluded from the plasma, a condition which tends to occur experimentally. We give an example of a flux - including equilibrium which is unstable to tearing modes. Thus, the break-up of a current ring may be due to true instability, rather than a lack of equilibrium.

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2B25

2-D NUMERICAL CALCULATIONS OF FIELD REVERSED PLASMAS

R.D. Milroy
Mathematical Sciences Northwest, Inc.
Bellevue, Washington 98009
and
J.U. Brackbill
Courant Institute of Mathematical Sciences
New York, New York 10012

The formation of a field reversed, theta pinch plasma is simulated by the numerical solution of the time-dependent, nonlinear equations for magnetohydrodynamic flow on an adaptive computation mesh.[1]

The calculations simulate the theta-pinch implosion, formation of closed field regions, and subsequent axial compression phases of the compact torus experiments presently underway at Mathematical Sciences Northwest, Inc. and Los Alamos Scientific Laboratory. Using a specially rezoned Lagrangian mesh, a vacuum field solver, and an implicit formulation of the equations of motion, the configuration of the experiments has been accurately represented, including finite coil length, coil geometry, current history, resistive field diffusion and thermal conduction.

Simple analytic models predict that delayed field line reconnection can result in enhanced plasma heating and enlarged separatrix radii. Numerical calculations were performed to study this process using cusp coils at the ends to delay reconnection, and fast mirror coils to trigger reconnection when desired.

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[1] J.U. Brackbill and W.E. Pracht, J. Comp. Phys. 13, 455 (1973).

2B26

Application of a Unified Theory to the Charged-Particle Slowing-Down in Superdense Fusion Plasmas

M-Y Hsiao and C. K. Choi
Fusion Studies Laboratory
Nuclear Engineering Program
University of Illinois
Urbana, Illinois 61801

The relaxation phenomena of charged particles in fusion plasmas formulated by unified theory are discussed. Charged-particle slowing-down mechanism in a plasma is usually treated from one of the three theories: binary-collision theory,(1) wave theory,(2) and the unified theory.(3) Basically, the binary-collision theory treats a plasma as a rarefied gas; wave theory regards a plasma as a continuous dielectric medium. Ad hoc cutoff is introduced in both theories.

Unified theory is a unique approach in that it gives a convergent energy-loss rate for the corresponding convergent process without any artificial cutoff. This is because the unified theory uses a correct treatment on the dual nature of a plasma while the other two theories do not. Calculations show that the error which binary-collision theory gives increases with the plasma number density and decreases with the plasma temperature. In high-density plasmas, for example, at T = 1 keV, $n_e = 10^{25}cm^{-3}$, for 50-50 D-T plasma, the errors in both slowing-down time and energy-loss rate can be up to over 20%.

The dependence of the error on the plasma temperature becomes more sensitive as the plasma number density increases; in fact, at $n_e = 10^{15}cm^{-3}$ with T = 1 keV, difference between the unified formalism and the collisional theory is about 5% for slowing-down times and the energy-loss rate, thereby the unified theory assures the conventional use of the collisional theory at this plasma range. Both theoretical and numerical studies indicate, however, that due to wide range of validities and consideration of plasmas, the unified theory will give better accuracy whether plasmas are in high-density or in low-density, or hot or cold; still, in most cases the unified calculation requires almost the same amount of computer time. This unified treatment is considered to provide a viable method in high-energy charged-particle transport in fusion plasmas.

1. D. V. Sivukhin, Reviews of Plasma Physics, Vol. 4, p. 93, Consultants Bureau, New York (1966).
2. D. Pines and D. Bohm, Phys. Rev., 85, 338 (1952).
3. Y. Itikawa and O. Aono, Phys. Fluids, 9, 1259 (1966).

2B27

NEO-CLASSICAL TRANSPORT COEFFICIENTS IN THE PLATEAU REGIME FOR ARBITRARY CROSS SECTION AND BETA*

H. K. Meier and D. J. Sigmar

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

While numerous authors have calculated the neo-classical transport coefficients for deformed cross sections in the banana and Pfirsch-Schlüter limits it is difficult to do this for general equilibria in the plateau regime. Even for a circular cross section, the proper inclusion of the mirroring term in the drift kinetic equation is subtle[1].

It has been found that a poloidal angle θ exists such that tokamak flux surfaces can be represented by expressions of the form

$$R(\psi,\theta) = R_o(\psi) + U(\psi)\cos\theta + \sum_{m=z}^{\infty} D_m(\psi)\cos m\theta,$$

and

$$Z(\psi,\theta) = E(\psi)[U(\psi)\sin\theta - \sum_{m=z}^{\infty} D_m(\psi)\sin m\theta].$$

These expansions converge very rapidly. $m \leqslant 3$ is found in practice to be sufficient even for a high β, strongly D shaped plasma.

Using this representation the ion drift kinetic equation in the plateau regime has been solved compactly for the general class of equilibria described by the above equations. The transport coefficients will be evaluated.

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

[1] S. P. Hirshman and D. J. Sigmar, Phys. Fluids 20, 418 (1977).

2B28

Functional Integral Approach to Classical Statistical Dynamics*

R. V. Jensen and C. Oberman
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

A functional integral method is developed for the statistical solution of nonlinear stochastic differential equations which arise in classical dynamics. The functional integral approach provides a very natural and elegant derivation of the statistical dynamical equations that have been derived using the operator formalism of Martin, Siggia, and Rose.(1) More importantly, it is easily extended to a broad, new class of nonlinear dynamical equations with random coefficients. In particular, the equations of motion for the correlation and response functions are determined for classical systems with non-Gaussian initial conditions, multiplicative random forces, and nonlinear interactions which are non-local in time. These results have applications in the calculation of particle motion in stochastic magnetic fields, in the solution of stochastic wave equations, and the description of electromagnetic Vlasov turbulence.

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*Work supported by U.S. DoE Contract No. DE-AC02-76-CH03073 and by U.S. AFOSR Contract PR #80-00656.

[1] P. Martin, E. Siggia, H. Rose, Phys. Rev. A8, 423 (1973).

DIFFUSION AND MAGNETIC ENERGY DISSIPATION IN FIELD REVERSED PLASMAS*

J. D. Huba
Science Applications Incorporated
McLean, Virginia

and

J. F. Drake and N. T. Gladd
University of Maryland and Naval Research Laboratories

The resistive diffusion of plasma density and magnetic field profiles in a one dimensional system of arbitrary β has been studied. For isothermal plasmas in quasi-equilibrium (local pressure balance), a simple diffusion equation in flux coordinates describes the complete time evolution of the profile. Our investigations have important implications in understanding the nonlinear saturation of current driven microinstabilities (e.g., the lower hybrid drift instability) and anomalous transport in general.

In a finite β plasma, the particle drifts and magnetic field are coupled and, consequently, the anomalous dissipation of the particle drift energy and magnetic energy are also linked. The magnetic field therefore effectively acts as a source of free energy to destabilize microinstabilities. This magnetic free energy exceeds the particle drift energy when $\beta > (m_e/m_i)(v_{di}/v_i)$, v_{di} and v_i being the ion diamagnetic and thermal velocities. Estimates of the saturation of instabilities based on the drift energy bound and their associated transport coefficients are invalid.

The evolution field reversed plasmas with model resistivities based on the nonlocal structure of the lower hybrid drift instability ($\nu=0$ at $B=0$) has been studied numerically. Magnetic flux diffuses toward the neutral line ($B=0$), dramatically increasing the local current density in this region. The current density near $x=0$ is expected to increase until the lower hybrid drift mode can penetrate the high β region near $x=0$. The subsequent rapid annihilation of the magnetic flux may be responsible for the bursting phenomena reported in magnetic substorms. We discuss the implications of our results for reversed field theta pinches and mirrors.

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ANALYTIC MIRROR EQUILIBRIUM STUDIES*

D. A. D'Ippolito and J. P. Freidberg
Science Applications, Inc.
Plasma Research Institute
Boulder, Colorado 80302

As a preliminary step to understanding the ballooning stability of the tandem mirror configuration, we have attenpted to find some useful analytic equilibrium solutions of the three-dimensional MHD equations. We expand the equations in the small parameter $\delta = R_m - 1$, where R_m is the mirror ratio on axis. For the scalar pressure case, the imposition of periodicity constraints leads to a closed set of equations, one of which has a form similar to the 2D Grad-Shafranov equation. After choosing two free functions of the flux, these equations can be solved analytically. For the anisotropic pressure case, the same sort of analysis can be carried out, although to simplify the algebra we introduce the long-thin approximation at the outset. A possible application of this model is to the minimum-B end plug of the tandem mirror experiment where $\delta \approx 1/3$.

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poster

2B31

Numerical Simulations on Poloidal Divertors*

T. Takizuka+, H. Okuda and W. W. Lee
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

A 2½-dimensional particle simulation code has been developed to study the particle and energy flows into a poloidal divertor in the presence of self-consistent electrostatic potential along the field lines. The magnetic field topology, which has a separatrix and scrape-off layers, is generated by two straight line-filaments modeling both the plasma and divertor currents. Both ions and electrons are treated as discrete particles and their motive along the field lines is followed using

$$\frac{dv_{\|}}{dt} = \frac{q}{m} E_{\|} \qquad ,$$

while the motion across the field lines is modeled by a diffusion process using a Monte Carlo technique in which an ad-hoc diffusion coefficient is assumed. Preliminary results of simulations indicate the build up of ambipolar potential near the neutralizing plate reaching $e\phi/T_e \approx 0.5$ with the shielding length of the order of 5 Debye lengths. The average flow speed for the particles is about the sound speed, v_s. However, the electron flow speed exceeds this value considerably near the neutralizing plate. The width of the scrape-off layer is also measured and found to be consistent with the scaling of $(D_{\perp}/v_s)^{\frac{1}{2}}$ where $D_{\perp}$ is the cross field diffusion coefficient.

Effects of particle trapping due to the magnetic field gradient is being built in the code and the result will be reported.

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

+ Permanent address: Japan Atomic Energy Research Institute, Tokai, I baragi, Japan

ORAL presention desired.

2B32

Anomalous Ion Thermal Conductivity From Drift Waves

Wendell Horton

Fusion Research Center
The University of Texas at Austin
Austin, Texas 78712

Dieter Biskamp

Max-Planck Institut fur Plasmaphysik
8046 Garching
Federal Republic of Germany

Abstract

Linear toroidal drift mode theory predicts a ballooning drift wave instability with a growth rate proportional to the geometric mean of the ion pressure gradient and the unfavorable magnetic curvature. The maximum growth occurs for $k_\perp \rho_i \lesssim (1+\eta_i)^{-\frac{1}{2}}$ and exceeds the ion transit frequency. The electron response is adiabatic and quasilinear. For the faster growing linear modes formulas for ω_k, γ_k are obtained and compared with the values obtained from the shooting code for variations in ξ, η_i, and ϵ_n. In the nonlinear regime there is a strong turbulent convective mixing of the ion thermal energy density. Nonlinear theory and fluid simulations are used to investigate the mode coupling and anomalous transport. In the turbulent state we find that the ion thermal conductivity varies as $\chi_i \cong \hat{\chi}(cT/eB)(\rho/r_n)q(1+\eta_i)^{\frac{1}{2}}/\xi$ which scales like, but exceeds by $(R/\xi r_n)$, the neoclassical plateau value. The anomalous transport is investigated through 3D slab simulations[1] and a simplified 2D toroidal mode coupling model[2]. Simply renormalized mode coupling theory is applied to obtain a model wavenumber spectrum and the time behavior of $\langle \varphi^2 \rangle$ and $\langle \delta p^2 \rangle$.

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This work is supported by the U.S. Department of Energy Contract DE-AC05-79ET-53036.

ORAL

2B33

Reconnection, Compression and Tilting of a Reversed Slab Theta-Pinch with Endloss

F. Brunel, T. Tajima and J. M. Dawson
University of California, Los Angeles

Much improvements in the outflow but also in the plasma heating are seen when we reverse the magnetic field inside a long high-β column in radial pressure equilibrium[1]. Simulations have been performed in the slab geometry with a 2 1/2 D particle MHD code with $\gamma = 2$ (γ is the adiabatic constant). At $t = 0$, the column has sharp boundary and the internal and external magnetic fields have opposite direction; the end losses are treated by taking lost particle out of the system. As the plasma goes out, the magnetic field lines reconnect at the end and two elongated magnetic islands are formed, which close the field geometry and reduce subsequent endloss. As time goes on, the trapped plasma is adiabatically compressed toward the center of the column with a large transfer from magnetic to plasma energy as the magnetic islands reduce their aspect ratio to R, the ratio of the length L of the island over the radius a of the column. Although the island system is still prolate in later times, one of the islands which is compressed faster, displaces the other from its equilibrium position and the system becomes tilted[2]. In the slab geometry the other island is broken up at this stage.

This work was supported by DOE.

[1] F. Brunel, T. Tajima, J. N. Leboeuf and J. M. Dawson, Bull. Amer. Phys. Soc., 24, 1008 (1979).

[2] M. N. Rosenbluth and M. N. Bussac, Nucl. Fusion, 19, 489 (1979).

POSTER SESSION REQUESTED

2B34

THE VELOCITY DISTRIBUTION OF ALPHA PARTICLES AND COLLISIONAL HEATING IN THERMONUCLEAR PLASMAS[†]

J. D. Gaffey, Jr.*
Plasma Physics Division
Naval Research Laboratory
Washington, D.C. 20375, U.S.A.

R. S. Schneider
Instituto de Física
Universidade Federal do Rio Grande do Sul
90000 Porto Alegre, RS, Brasil

The velocity distribution of alpha particles produced at a constant rate by thermonuclear reactions in a Maxwellian plasma is obtained analytically and numerically from the Fokker-Planck equation. The time-asymptotic distribution may be divided into three regions: a thermalized region with a nearly Maxwellian distribution, a slowing-down region with a power law distribution, and a high-energy region with a rapidly decreasing exponential distribution. A more detailed treatment, including the time evolution, a loss term and a weak parallel electric field is given for the slowing-down region, which contains the majority of the alpha particles. The time evolution is also found for the high-energy tail. The time evolution of the density of particles, momentum density, kinetic energy density and heat flux density is calculated. The electron and background ion contributions are given separately to show the effects of each species. In particular it is found that the electrons are more rapidly heated by the alpha particles than are the background ions.

[†] Supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (FINEP) and National Research Council (NRC).

* NRC/NRL Research Associate

2B35

SIMULATION OF HEATING EFFICIENCY BY LOWER HYBRID WAVES

V. K. Decyk, J. M. Dawson, an G. J. Morales, UCLA

A survey of the efficiency of plasma heating by lower hybrid waves as a function of applied power is made with an electrostatic particle simulation on the UCLA CHI computer system. This interactive minicomputer[1] performs high-speed computations at low cost, and this has allowed longer runs with more detailed diagnostics than previously attempted.[2] The lower hybrid wave is excited by external sources and the efficiency of wave excitation (coupling) is compared with the efficiency of particle heating (absorption). Spatial profiles of power absorption are obtained to distinguish between surface and interior heating.

This work was supported by USDOE and ONR.

[1] J. M. Dawson, R. W. Huff, and C. C. Wu, AFIPS Conf. Proc. Natl. Comp. Conf., 47, 395 (1978).

[2] V. K. Decyk, G. J. Morales, and J. M. Dawson, Phys. Fluids, 23, April, 1980.

2B36

Noncanonical Hamiltonian Density Formulation of Hydrodynamics and Ideal MHD*

P. J. Morrison and J. M. Greene
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

We present a new Hamiltonian density formulation for a perfect fluid with or without a magnetic field. Contrary to previous work the dynamical variables used here are the physical variables, ρ, $\underset{\sim}{v}$, $\underset{\sim}{B}$, and S, which form a noncanonical set. A Poisson bracket, which is a bilinear antisymmetric operator on functionals, is defined and shown to satisfy the Jacobi identity. This bracket, together with a Hamiltonian density (equal to the energy density of the fluid), formalizes ideal MHD including entropy convection. Inviscid hydrodynamics is a special case of this formalism. We transform this Hamiltonian density formulation to an ordinary Hamiltonian system whose set of dynamical variables is the countably infinite set of Fourier coefficients obtained from spatial Fourier decomposition of the Eulerian fluid variables.

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A Mechanism for Energetic Ion Losses in Tokamaks

F.L. Hinton

Fusion Research Center
The University of Texas at Austin
Austin, Texas 78712

Abstract

Some effects of toroidal field ripple on energetic charged particle orbits in Tokamaks are considered. A finite Larmor radius generalization of the ripple-trapping condition is derived. Conditions are given for the existence of cyclotron resonances with the fundamental and harmonic Fourier components of the ripple field. Conditions on the magnitudes of these Fourier components are derived, such that the phase space islands corresponding to the cyclotron resonances overlap the ripple-trapping region. The intrinsic orbit stochasticity resulting from resonance overlap may be described as pitch-angle scattering; the diffusion coefficient is derived from an approximate mapping. Particles not initially ripple-trapped may thus diffuse into the ripple-trapping region, or co-moving particles ($\vec{v} \cdot \vec{j} > 0$) may become counter-moving particles ($\vec{v} \cdot \vec{j} < 0$). Such particles are subsequently lost on the drift time scale. For 3.5 Mev α-particles, the resonance and overlap conditions may be satisfied only in devices with relatively small toroidal fields or major radii. If ions of somewhat higher energies are injected directly, in order to heat a large tokamak plasma to ignition, they could be susceptible to this loss mechanism.

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2B38

Energy Principle with Global Invariants*

A. Bhattacharjee, R. L. Dewar, and D. A. Monticello
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

A variational principle is proposed for constructing equilibria with low free energy in toroidal plasmas where relaxation is dominated by a tearing mode of single helicity (specifically, the n = 1, m = 1 mode). States with toroidal current vanishing on the boundary, and with nonzero pressure gradients, can be constructed in this model. Theoretical predictions are compared with experimental data from reversed-field pinches and tokamaks.

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

2B39

DIFFUSE BOUNDARY EQUILIBRIA FOR THE BYU TOPOLOTRON EXPERIMENT

by

S. Neil Rasband
and
Darrell Peterson

Brigham Young University
Provo, Utah 84602

A numerical code has been developed for integration of the Grad-Shafranov equation giving diffuse boundary equilibrium solutions for the BYU Topolotron experiment. The code uses the familiar SOR Modified-Picard technique to converge to equilibria exhibiting the limit cycles of the topolotron configuration with two oppositely directed plasma current channels. Equilibria for assorted choices of the experimental parameters, in the range available to the experiment, and a variety of profiles have been computed. No stability study has yet been undertaken.

2B40

Kinetic Effects on Ballooning Modes*

J.W. Connor,† R.J. Hastie,† and W.M. Tang
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

Recent experimental results[1] on tokamaks have shown no evidence of the critical β limit predicted for the stability of MHD ballooning modes, suggesting either that they are stabilized by kinetic effects or that their nonlinear consequences are not serious. In this paper, we address the first possibility. Using the ballooning formalism, appropriate for high mode number perturbations of plasma in a sheared toroidal magnetic field, we solve the Vlasov-Maxwell equations for modes with perpendicular wavelengths comparable to the ion gyroradius. The local stability is, then, determined on each flux surface by the solution of three coupled integro-differential equations which include the effects of magnetic field compression, finite gyroradius, trapped particles, and wave-particle resonances. These equations can be simplified in the limits $\omega < \omega_{bi}$ and $\omega > \omega_{bi}$ where ω_{bi} is the ion bounce frequency. Since at marginal stability, it is expected that $\omega \sim \omega_*$ where ω_* is a diamagnetic drift frequency, the appropriate limit depends on the wavenumber of the mode. If we further assume $\omega > \omega_d$ where ω_d is the magnetic drift frequency, trapped particle effects are weak and can be reduced to a single second-order differential equation. Its form differs depending whether $\omega \gtrless \omega_{bi}$, but in either case it reduces to an appropriate limit of the MHD equations corresponding to $\omega \lesseqgtr \omega_s$ where $\omega_s = c_s/L_c$ with c_s being the sound speed and L_c being the connection length.

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†Culham Laboratory, Abingdon, Oxon, OX14 3DB, UK (Euratom/UKAEA Fusion Association)

[1] D.W. Swain, et al., 9th European Conf. on Controlled Fusion and Plasma Physics (Oxford, Sept. 1979), paper B2.2; H.P. Furth (Oxford Conf.), invited paper B1.4 (1979).

2B41

Power Absorption of Lower Hybrid Waves near Mode Conversion in the Presence of Ion Cyclotron Harmonics

Kwok Ko, V. Fuchs,[†] A. Bers
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

Numerical solutions of a local dispersion relation (∇n, ∇B, ∇T) for tokamak parameters show that the mode conversion from lower hybrid to warm plasma wave is significantly modified by the ion cyclotron harmonics and the usual biquadratic warm plasma dispersion relation is inadequate to describe the wave characteristics under such conditions. By Taylor expanding the full dispersion relation about the perpendicular wave number for which the group velocity vanishes, we obtain a quadratic dispersion relation for the two coupled modes. This approximate dispersion relation agrees well numerically with the exact dispersion relation in the mode conversion region. The corresponding second-order differential equation defines a two turning-point propagation problem which is solved by WKB techniques. We find the transmission and reflection coefficients by numerically evaluating the complex turning points. Damping due to the ion cyclotron harmonics is then deduced by invoking energy conservation. We integrate this result over a typical lower hybrid wave spectrum to estimate the amount of power absorbed.

*Work supported by U. S. Department of Energy Contract No. ET78-S-02-4682.

[†] On leave from Institut de Recherche de l'Hydro-Quebec.

Nonlinear Evolution of Tearing Instabilities: Coalescence of Magnetic Islands*

C. C. Wu

Center for Plasma Physics and Fusion Engineering
University of California, Los Angeles, California

A numerical analysis has been conducted of the coalescence instability of magnetic islands which are formed during the nonlinear evolution of tearing modes. The parallel currents in neighboring islands are found to coalesce into larger units with growth rates faster than those for linear tearing modes. The characteristics of the coalescence process are similar to those found for an exact hydromagnetic equilibrium consisting of an infinite chain of magnetic islands.[1] During the coalescence process, a bulk displacement of the current filaments with local Alfven speed occurs and the kinetic energy is increased by two-order-of-magnitude from the saturation level of the tearing modes. The magnetic islands formed after the merging are also subject to the coalescence instability, which increases the kinetic energy further. Together with the coalescence processes, the tearing instabilities may therefore account for various explosive phenomenon such as internal m=1 disruptions in tokamaks, solar flares and magnetospheric substorms.

*Work supported by USDOE

[1] P. L. Pritchett and C. C. Wu, Phys. Fluids 22, 2140 (1979).

POSTER SESSION REQUESTED

POSTER SESSION

NONLINEAR THEORY OF HIGH-m TEARING MODES

R. R. Dominguez, M. Rosenberg, and C. S. Chang

General Atomic Company
San Diego, California 92138

ABSTRACT

A nonlinear theory of short wavelength (high-m) electron temperature-gradient-driven tearing modes is presented. Saturation of the linear instability results from nonlinear mode coupling in k space. Energy may cascade to both shorter and longer wavelengths in the mode coupling process. The resulting steady-state electron thermal conductivity exhibits the density scaling and absolute magnitude experimentally observed.

Work supported by Department of Energy, Contract DE-AT03-76ET51011, GA Project No. 3235.

2B44

IDEAL AND RESISTIVE MHD STABILITY COMPUTATIONS FOR A FINITE-LENGTH CYLINDRICAL SPHEROMAK*

George J. Marklin and C. S. Liu
Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20742

John M. Finn
Science Applications, Incorporated
McLean, Virginia

To model the paramagnetic spheromak at the University of Maryland, a finite-length cylindrical plasma with a conducting wall boundary is used for a numerical stability analysis.

The solution of the force-free equilibrium equation $\nabla \times \vec{B} = \lambda \vec{B}$ obtained by the conventional method of separation of variables satisfying the boundary condition $\vec{B} \cdot \hat{n} = 0$ is a cylindrically symmetric m=0 state. To examine the stability of the lowest energy symmetric state, ideal and resistive linear MHD codes have been written.

It is found that an m=1 tilting instability occurs when the elongation L/R exceeds 1.68. This critical value agrees with that obtained by An, et al. (this proceeding) for the crossover of the magnetic energy for the m=0 and m=1 modes.

A second m=1 mode becomes unstable when the q=1 surface first appears, at $L/R \sim 1.8$. It attains a maximum growth rate of about .2 τ_A^{-1} when $L/R \sim 3.1$, the point where the q=1 surface disappears.

Additional results, including the effects of finite beta and resistivity, will also be presented.

*Supported by U.S. Department of Energy.

2B45

Nonlinear Saturation of Current Driven Drift Waves

Amiya K. Sen*, T. Tange†, and K. Nishikawa†

We have studied the nonlinear saturation of current driven drift waves in Tokamak like devices. The basic nonlinear equation contains the usual linear terms including the shear induced term and the polarization drift nonlinearity. By expanding the wave potential in terms of linear sheared eigenfunctions involving zero (n = 0) and first order (n = 1) Hermite functions, we obtain mode (m) coupling equations. The n = 0 modes couple among themselves to produce n = 1 modes which are stable, thus providing a nonlinear saturation mechanism. The general problem involving two sets (n = 0,1) of many coupled modes has been reduced to a single integral equation in the spectral density I of n = 0 modes. Stationary solution of the spectrum has been obtained as $I(k) = c_1\bar{k}^{-3.3} + c_2\bar{k}^{-2.5+i.7} + c_3\bar{k}^{-2.5-i.7}$ where $\bar{k}$ is the poloidal wave number (m/r) normalized with respect to ion gyroradius based on electron temperature and considered as a continuous variable. The constants c_i are determined from certain consistency relations. The nonlinear saturation mechanism proposed here resolves the paradox of unlimited accumulation of wave energy in the lowest wave number mode in the weak turbulence theory.

One of the authors (AKS) has been supported in part by a National Science Foundation Grant NSF-ECS-7917033.

† Physics Department, Hiroshima University, Hiroshima, Japan

* Department of Electrical Engineering and Plasma Research Laboratory, Columbia University, New York, N.Y.

Note: (Not to be reproduced in the Proceedings) Submitted by: A. K. Sen (A.K. SEN) 3/31/80.

Earnestly request that this paper be scheduled for a session on April 24 or 25 and definitely not on April 23. I have to attend an important meeting on April 23.

2B46

FREE ELECTRON LASER WITH A STRONG ELECTRIC FIELD*

Y. P. Ho, Y. C. Lee†
and
M. N. Rosenbluth
Institute for Advanced Study, Princeton, New Jersey 08540

ABSTRACT

We have demonstrated, through analytical and numerical means, that it is possible to improve the efficiency of the free electron laser by using a combination of a strong longitudinal electric field and an adiabatically varying ripple magnetic field. In some cases, near 100% trapping efficiency has been obtained. Neglecting the effects of untrapped particles and the bounce motion of the trapped ones in the ponderomotive potential well, a self-consistent field equation has been derived. The equation can be trivially integrated in the one-dimensional case. In the two and three dimensional cases where effects due to diffraction become important, the equation has been solved by numerical integration. Analytical solutions have been obtained for the special two-dimensional case where there is a lossy medium, as well as for the case where longitudinal electric field is assumed to vary in a prescribed manner.

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†Also Laboratory for Plasma and Fusion Studies, University of Maryland.

Rotation Model for FRθP*

Q. T. Fang and G. H. Miley
Fusion Studies Laboratory
Nuclear Engineering Program
University of Illinois
Urbana, Illinois 61801

The mechanism of plasma rotation in field-reversed theta pinch (FRθP) has long been argued.(1,2) A two-fluid rigid rotation model, based on the conservation of canonical angular momentum and radial particle and energy losses, was first proposed to account for the plasma azimuthal acceleration (spin-up), which eventually limits the plasma lifetime due to the m=2 rotational instability.(3) This model gives favorable results compared with the experimental data from FRX-A.(3) The transport model, currently assumed in this rotation model, is a classical scaling, or one corresponding to the lower-hybrid-drift instability, both multiplied by a numerical factor of about 20 ~ 30 to fit the observed particle confinement time of ≈ 80 μs. Loss-cone scattering is being considered as a possible major mechanism for the relatively short confinement time observed. A Fokker-Planck treatment has been adopted to investigate this mechanism. The major mechanisms that affect the plasma rotation have been identified as (a) the $\vec{J}_{\perp\alpha} \times \vec{B}$ bulk force which has a positive effect on plasma rotation, where $\vec{J}_{\perp\alpha}$ is the radial leakage current of ions (α=i) or electrons (α=e); (b) the resistive drag between ions and electrons, which always has a negative effect on rotation; (c) the temperature decay or the energy loss. The latter gives rise to a decay in the total magnetic flux and according to the conservation of canonical angular momentum the rotation speed $|\omega|$ has to increase. Consequently, understanding of the more exact transport behavior is essential to obtain better results.

*Work supported by U. S. DOE Contract No. DE-AS02-76ET52040.

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2. D. C. Barnes and C. E. Seyler, Sym. on Compact Torus and Energetic Particle Injection, Princeton, NJ, Dec. 1979.

3. R. K. Linford, et al., Conf. Plasma Phys. and Contr. Nucl. Fusion Res., Innsbruck, Austria, 2, 447 (1978).

DIMENSIONALITY AND LYAPUNOV NUMBERS OF STRANGE ATTRACTORS*

Edward Ott and James Hanson
University of Maryland
College Park, Maryland 20742

David A. Russell
Cornell University
Ithaca, New York 14850

The (Hausdorf) dimension of a strange attractor is of practical interest since it specifies the amount of information necessary to define the location of a strange attractor to within a prescribed accuracy and thus also to specify a coarse-grained strange attractor distribution function. Here we investigate the possibility that the dimension can be determined from the Lyapunov numbers of the strange attractor.[1] Examples concerning problems in plasma physics will be used to test this hypothesis.

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

[1] J. A. Yorke, private communication.

2C2

Drift Modes in the Central Cell of Tandem Mirrors

Wendell Horton

Fusion Research Center
and Department of Physics
The University of Texas at Austin
Austin, Texas 78712

Abstract

In the axisymmetric, long-thin, approximation the symmetric and antisymmetric axial drift modes are investigated. For the system parameters, L_c/r_n, ρ_i/r_n, β we consider $L_c/r_n \sim r_n/\rho_i$ and three pressure regimes (1) $\beta \sim (r_n/L_c)^2$, (2) $\beta \sim (r_n/L_c)$, and (3) $\beta \sim (r_n/L_c)^0$. In regime (2) the electron drift wave is transformed through coupling to the shear-Alfvén wave to a finite frequency convective cell. In regime (3) only the FLR-MHD mode appears important. Quasilinear particle and thermal flux formulas are derived including $\delta B_{\|}$, $E_{\|}^{(A)}$ and ϕ with estimates given for D and χ.

Due to the relatively small number of unstable modes, applicability of quasilinear theory is questioned. Following the analysis of Kishinevskij, et al.[1] for the SEM device, the single particle equations of motion are analyzed for resonant and stochastic motions in the presence of a few drift modes.

[1] M.E. Kishinevskij, et al., IAEA-CN-37/J-3 (1979).

This work is supported by the U.S. Department of Energy Contract DE-AC05-79ET-53036.

ALPHA PARTICLE DRIVEN COMPRESSIONAL AFLVÉN WAVE INSTABILITY IN A TANDEM MIRROR REACTOR*

James D. Hanson and Edward Ott
Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20742

Because their energies greatly exceed the plug potential, fusion reaction alpha particles in a Tandem Mirror Reactor will be mirror confined rather than electrostatically confined by the end plugs. Hence, the alpha particle distribution function will have a loss cone. This anisotropy in the distribution function is shown to destabilize compressional Alfvén waves in the central section of a Tandem Mirror Reactor.

We use the compressional Alfvén wave dispersion relation with resonant particle effects included. The alpha particle distribution function is an approximate solution to the steady state Fokker-Planck equation,[1] with a loss cone. A simple model of the radial variation of the Alfvén speed is used to choose appropriate $k_\perp$ values for the dispersion relation. Because the Alfvén speed becomes large at the mirror throats, the central cell is expected to be a resonant cavity for the unstable compressional Alfvén wave.

Destabilization of the wave occurs due to a cyclotron resonance of the alpha particles. The resonant interaction of the wave with the alpha particles will pitch-angle scatter the alphas into the loss cone. The lost alpha particle energy will thus be unavailable for plasma heating and must be externally supplied to the plasma. As a result, the Q for a typical Tandem Mirror Reactor[2] may drop substantially. Estimates of the Q degradation will be presented.

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

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[2] B. M. Boghosian, D. A. Lappa, B. G. Logan, Lawrence Livermore Laboratory Report UCID-18314 (1979).

2C4

TEARING-MODE STABILITY PROPERTIES OF A FIELD-REVERSED ION LAYER AT MARGINAL STABILITY†

James Chen and Ronald C. Davidson
Plasma Fusion Center
Massachusetts Institute of Technology, Cambridge, Mass. 02139

This paper investigates a variety of Vlasov equilibrium and stability properties of a rotating nonrelativistic, cylindrically symmetric ion beam propagating parallel to a uniform applied magnetic field through a background plasma. These studies include (a) investigations of the thermal equilibrium properties of an intense ion beam propagating through a background plasma, and (b) tearing-mode stability properties of a field-reversed ion layer. For example, the tearing-mode stability properties are investigated at marginal stability (ω=0) for a rotating, nonrelativistic cylindrically symmetric ion layer immersed in an axial magnetic field $B_z^0(r)\hat{e}_z = [B_0 + B_z^s (r)]\hat{e}_z$. The analysis is carried out within the framework of a Vlasov-fluid model in which the electrons are described as a macroscopic, cold fluid, and the layer ions are described by the Vlasov equation. Tearing-mode stability properties are calculated numerically for azimuthally symmetric perturbations about an ion layer equilbrium described by $f_i^0 = \text{const} \times \exp[-(H + \omega_0 P_0)/T]$. Here, H is the energy, P_θ is the canonical angular momentum, T=const is the temperature, $-\omega_\theta$=const is the angular velocity of mean rotation, and the density profile is $n(r) = n_0 \text{sech}^2\ (r^2/2\delta^2 - r_0^2/2\delta^2)$, where $\delta^4 = 2c^2T/(m_i\omega_\theta^2\omega_{pi}^2)$ and $\omega_{pi}^2 = 4\pi n_0 e^2/m_i$. The marginal stability eigenvalue equation for the perturbation amplitude $\hat{A}_\theta(r)$ has the form of a Schroedinger equation, with "energy" eigenvalue $k_z^2\delta^2$ and effective potential $V(r) = \delta^2/r^2 - 2(r^2/\delta^2)\text{sech}^2\ (r^2/2\delta^2 - r_0^2/2\delta^2)$. This equation is solved numerically for $\hat{A}_\theta(r)$ and the normalized axial wave number at marginal stability (denoted by $k_0^2\delta^2$) as a function of normalized layer radius r_0/δ and magnetic field depression $\beta_i^{-1/2}[B_0-B_z^0(r=0)]/B_0$, where $\beta_i = 8\pi n_0 T/B_0^2$. For $r_0^2/\delta^2 > 1$, the numerical analysis shows that $k_0^2\delta^2$ can be approximated by $k_0^2\delta^2 = r_0^2/\delta^2$ to a high degree of accuracy.

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2C5

Temporal Evolution of Nonlinear Lower-Hybrid Waves*

Charles F. F. Karney

Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

The nonlinear evolution of a single lower-hybrid wave in two dimensions and time is considered. The plasma is taken to be homogeneous and the fields to be electrostatic. Early work[1-3] treated the steady-state problem in which the potential was assumed to have the form $\phi(x,z)\exp(-i\omega t)$. However, when the boundary conditions are correctly imposed, the resulting equation is ill-posed.[3] This defect can be corrected by allowing a slow temporal variation so that the potential is given by $\phi(x,z,t)\exp(-i\omega t)$. The equation describing the fields is then

$$iv_\tau - \int v_\xi \, d\zeta + v_{\zeta\zeta} + |v|^2 v = 0 \qquad (1)$$

where v is proportional to the electric field, τ to time, and ζ and ξ measure distances across and along the lower-hybrid ray. The properties of Eq. (1) are investigated numerically. The domain of the problem is a strip $\xi_0 < \xi < \xi_1$. The boundary conditions are the incident wave at ξ_0 and the incident wave at ξ_1 which is taken to be zero corresponding to a radiation condition. The reflected and transmitted waves are determined. When the amplitude is sufficently large, three phenomena are observed: (1) The fields do not reach a steady state even though steady-state boundary conditions are imposed. (2) The density modulations are sufficient to cause an appreciable fraction of the incident power to be reflected. (3) The average wavenumber of the transmitted wave can be larger than that of the incident wave. Ignoring numerical factors, the conditions for these phenomena to occur are that the potential drop over a half-wavelength exceed the electron temperature and that the width of the nonlinear region exceed $\Delta x/\beta$ where Δx is the width of the ray in the x direction and β is the ratio of the electric field energy to plasma kinetic energy.

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* Work supported by U.S. DoE Contract #DE-AC02-76-CH03073.

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2. H.H. Kuehl, Phys. Lett. 61A, 235 (1977).
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2C6

Adiabatic Theory for a Single Nonlinear Wave in a Vlasov Plasma and an Explanation of Electron Holes

V. B. Krapchev and A. K. Ram
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

The one-dimensional Vlasov equation for the electrons has been solved for a general form of the potential and to all orders in the field amplitude [1]. For a given initial condition, the distribution function has been determined uniquely as a function of the action, which is the adiabatic invariant of the Vlasov equation. In contrast to the stationary solutions of Bernstein, Greene and Kruskal [2], we let the system evolve to its final stationary nonlinear state from a given initial state, thereby, eliminating the arbitrariness that exists in the BGK theory.

Our theory predicts the existence of a nonlinear mode below the plasma frequency whose dispersion relation is: $\omega = \omega_B = \sqrt{eEk/m}$, where E is the field amplitude and k is the wave number. The electrons trapped in the wave are primarily responsible for this mode. This trapped particle mode has been observed experimentally, and is called the "electron hole" [3]. The theoretical results we obtain are consistent with the experimental observations of these holes. The condition for a minimum potential for the existence of such a state is found to be $e\phi/T > 2.7$, where ϕ is the amplitude of the potential.

The theory can also be applied to a strongly magnetized plasma when only the electron dynamics along the magnetic field lines is important, as is the case of lower hybrid waves in a tokamak plasma [4]. The nonlinear modification to the distribution function generates steady-state currents. The scaling properties of such currents are examined.

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*Work supported by NSF Grant ENG77-00340 and U. S. DOE Contract ET-78-S-02-4682.

2C7

CONFLICTING CURRENT PROFILE REQUIREMENTS FOR IDEAL MHD STABILITY AND RESISTIVE DIFFUSION CONTROL IN A TOKAMAK*

L. A. Charlton, D. B. Nelson,+ R. A. Dory and D. K. Lee
Oak Ridge National Laboratory, Oak Ridge, Tennessee

It has been found[1] that a small ratio q_s/q_o (safety factory at the edge/safety factor at the magnetic axis) was desirable to minimize $\overline{\beta}_c$ in a tokamak plasma ($\overline{\beta} = 2 \int p d\tau / \int B^2 d\tau$ and the subscript c denotes the maximum value stable to ideal MHD modes).

For the stable equilibria in Ref. 1 the necessary conditions for them to be also in resistive steady state have been studied using the theory of Ref. 2 and Spitzer resistivity with constant Z_{eff}. Plasmas with small q_s/q_o require a broad or even hollow temperature profile in order to be in resistive steady state. Since the alpha particles in a reactor would be created preferentially at the pressure peak, the temperature would peak there also and not have a hollow profile. For cases studied, it proved necessary to raise q_s/q_o to ∿ 5 in order to obtain steady state equilibria with narrow peaked T_e profiles, unless a structured Z_{eff} is assumed. Therefore, the requirements of high $\overline{\beta}_c$ and control of resistive diffusion place conflicting demands on plasma properties.

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+Present Address: Office of Fusion Energy (ETM), Department of Energy Washington, DC.

[1] L. A. Charlton, et al., Phys. Rev. Lett. 43, 1395 (1979).

[2] D. B. Nelson and H. Grad, Oak Ridge National Laboratory Report No. ORNL/TM-6094.

2C8

STUDIES OF LOCAL MAGNETIC RIPPLE EFFECTS IN TOKAMAKS[*]

R. H. Fowler, J. A. Rome, V. E. Lynch and J. F. Lyon
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Effects of local magnetic ripple produced by the addition of external coils for bundle divertors and ripple injection have been studied. In particular, we have investigated effects due to ripple injection coils on ISX-B and a number of 2-coil and 4-coil bundle divertor configurations for INTOR/ETF, ISX-B and ISX-C. We have computed numerous guiding center orbits of ions and flux surfaces in a magnetic field composed of an axisymmetric equilibrium plus a vacuum ripple field. We have also investigated the effect of β on ripple by numerically solving the Grad-Shafranov equation for an axisymmetric cylinder encircled by external current loops.

From these studies we conclude:

(1) Since all banana trapped ions are confined to a region where $B \leqslant \varepsilon/\mu$, a local maximum in B may prevent the ion from drifting all the way around the torus and the ion may quickly ($<10^{-3}$ sec) "walk out" of the tokamak. In order to avoid mirroring of the bananas, the B surfaces must not shrink severely in a cross section near the ripple.

(2) Counter-circulating, as well as co-circulating ions near the plasma edge may be affected by local ripple.

(3) Only extremely high β ($\sim$100%) significantly reduces the amount of ripple due to a fixed external current.

(4) High β may exacerbate the ripple problem. The magnetic axis shifts outward into the high ripple region and a minimum in B may form in a region outside the magnetic axis when $\beta \gtrsim 6\%$. This causes the toroidal drift of bananas to stagnate where $\nabla B \to 0$ and increases their interaction time with the ripple.

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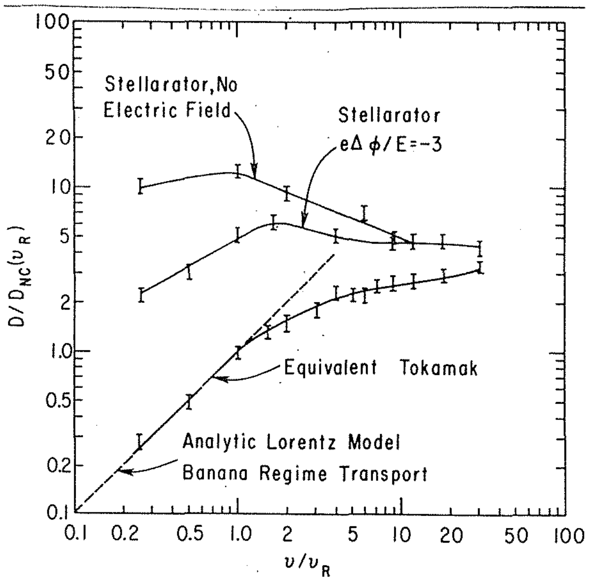
Poster Session

Monte Carlo Evaluation of Transport in Stellarators and Tokamaks with Ripple[*]

G. Kuo-Petravic and A. H. Boozer

Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

Bulk plasma transport coefficients of stellarators have been studied with a Monte Carlo code, and work has begun on tokamaks with ripple. We have found the stellarator ion heat conductivity depends weakly on collision frequency in the reactor regime and is enhanced over the tokamak neoclassical transport by roughly an order of magnitude. The stellarator and neoclassical tokamak transport coefficients for thermal ions are compared in the figure. The stellarator had $\ell = 2$, $M = 6$ with $q = 2$ on the surface that was studied. The magnetic field was 50kG, the minor radius 3 meters, and the aspect ratio 7. The reactor parameters are for $n = 3 \times 10^{14}$ cm^{-3} and $T = 9$kev. At a fixed collision frequency, the stellarator transport coefficients go as energy squared.



The Monte Carlo code follows particle drift orbits in a magnetic coordinate system. Collisions are simulated by the Monte Carlo equivalent of the Lorentz collision operator.

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[*] Work supported by U.S. DOE DE-AC02-76-CH03073.

2C10

Variational Formulation and Adiabatic Compression of Rotating Plasmas

D. Stevens, E. Hameiri, W. Grossmann
Courant Institute of Mathematical Sciences
New York University

We present a variational formulation for equilibrium states with flow, based on a full set of constants of the motion including one which reduces to angular momentum in the case of symmetry. This formulation can be used to derive an earlier known one[1] by the duality technique of the calculus of variations. Our formulation however is superior in that the functional is bounded below so that states can be obtained by minimization, while Ref. 1 generates saddle points.

Because the formulation is based only on constants of the motion, it is particularly useful for computing a sequence of equilibrium states obtained by a slow adiabatic compression, where the constants are unchanged but the boundary conditions are. In addition, the minimum property of the functional enables to do stability analysis. We extend the interchange stability criterion to rotating plasmas. Lastly, we present results of a numerical calculation for an adiabatically compressed, rotating mirror machine.

Work supported by U.S. DOE Contract DE-AC02-76ER0 3077.

1. J.M. Greene and E.T. Karlson, Phys. Fluids, 12, p. 561 (1969).

Oral presentation

(212) 460-7122 (E. Hameiri)

2C11

Plasma Heating by Magnetosonic Waves in High β Plasma*

K. Nozaki, B. D. Fried, G. J. Morales
University of California, Los Angeles

The possibility of heating high β plasmas such as a multipole plasma by the excitation of Alfven waves is examined. In low β plasmas, heating by a surface wave[1] or a magnetosonic eigenmode[2] at the shear Alfven wave resonance have been investigated previously. However, in high β plasmas the surface wave or the kinetic Alfven wave near the Alfven resonance point may be not effective because they mainly heat the plasma surface. The magnetosonic eigenmodes do not exist in high β plasmas because of the fairly large ion Landau damping rate. Magnetosonic waves excited by an external source propagate into the inner high β region and are absorbed there, heating ions mainly. Some part of the energy supplied by an external source is absorbed at the Alfven resonance point on the surface and the remaining portion of the energy is transferred into the main body of plasma by magnetosonic waves. Estimates are presented for the portion of the total energy supplied by an external source which can be transferred to the main body of the plasma beyond the Alfven resonance point.

*Work supported by USDOE.

[1] L. Chen and A. Hasegama, Phys. Fluids 17, 1399 (1974).

[2] E. Ott, J. -M. Wersinger and P. T. Bonoli, Phys. Fluids 21, 2306 (1978).

2C12

Electron Landau Damping of Loss-Cone Instabilities in a Mirror Reactor Regime

M. J. Gerver
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

A successful mirror reactor (either conventional or tandem mirror) must have a plasma short enough to be stable to the axial loss cone (ALC) mode, wide enough to be stable to the drift cone (DCLC) mode, of high enough β to be economical and to be stable to the negative energy wave (NEW), and with essentially empty loss cone. If finite electron temperature effects are ignored, no such equilibrium appears possible. In a reactor regime, however, $\omega_{be} \sim \omega_{ci}$, and (due to finite β) DCLC is only marginally flutelike, $k_{\|} L \sim 1$, so electron Landau damping can occur. Although the Landau damping decreases with increasing β, due to the increasingly transverse nature of the mode, the DCLC growth rate decreases even faster with β, and stabilization should occur at roughly $\beta > (m_i/m_e)^{1/3} \rho_i/L$, which is just possible in a reactor; hence a numerical calculation is required to see whether this stabilization will occur. For $\beta \sim 1$, $T_e << T_i$, $\rho_i/L << 1$, and $R_p \sim L$, we can use WKB perpendicular to the magnetic field, and solve the second order differential equation (including realistic geometry)

$$\left(1+\frac{\omega_{pe}^{4}}{k_\perp^{2}c^{2}\omega_{ce}^{2}}-\frac{\omega_{pe}^{2}}{k_\perp R_p\omega\omega_{ce}}\right)E_\perp+\frac{c^{2}}{\omega^{2}}\frac{d^{2}}{dz^{2}}E_\perp=0$$

along the field lines, with boundary conditions $dE_\perp/dz = 0$ at the mirror throats, to obtain a first approximation to the normal modes. The dielectric integral operator may then be inverted to obtain $E_{\|}$ in terms of $E_\perp$, and the small perturbation due to electron Landau damping may be calculated, to see if it can overcome the (small) growth due to the ion loss cone. Without ever having to solve an integral equation, we can find the stability conditions for a realistic 3-D equilibrium in a reactor regime. (The technique will not work for a low-β equilibrium or when $\rho_i \sim R_p$; in these cases an integral equation must be solved). The same method could be used to find ∇B drift damping due to a small component of hot ($T_e > T_i$) electrons, if bulk electron Landau damping is not sufficient for stability.

2C13

ANALYTIC REVERSED-FIELD MHD EQUILIBRIA AS "MOST PROBABLE STATES"

George Vahala, John Ambrosiano, and David Montgomery
College of William and Mary
Williamsburg, Virginia 23185

Recently, a procedure was given for selecting MHD equilibrium profiles[1] on a probabilistic basis. The idea was to assign a measure, or probability, to a particular set of equilibrium MHD fields, and to maximize this expression subject to certain constraints. These constraints were the constancy of various global integrals, such as energies, helicities, currents, or fluxes, which were to be regarded as known. The output of the variational calculation was a pair of coupled, highly nonlinear differential equations for the magnetic fields and/or potentials.

One limitation of our previous treatment was our apparent inability to recover reversed-field pinch configurations, such as the Lundquist-Taylor axisymmetric state in which B_z, B_θ are proportional to J_0 and J_1. Here we show explicitly how to remove this limitation. In a particular limit, the desired results are extracted analytically and in closed form. In addition, extensive numerical computations[2] have been carried out in limits in which the analytical procedures are not accurate.

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[1] D. Montgomery, L. Turner, and G. Vahala, J. Plasma Phys. 21, 239 (1979).

[2] J. Ambrosiano and G. Vahala (companion paper, this session).

2C14

MOST PROBABLE MHD EQUILIBRIA FOR TOKAMAKS AND REVERSED FIELD PINCHES

John Ambrosiano and George Vahala
College of William and Mary
Williamsburg, Virginia 23185

The determination of MHD equilibria requires the specification of two free functions. Since information available from experimental diagnostics is less than that required to specify these functions, they can then be considered random. Montgomery, Turner and Vahala[1] have recently proposed a statistical method for determining the free functions $B_z(r)$, $J_z(r)$ which are most probable when the global constraints of flux, current, energy and magnetic helicity are imposed on a symmetric incompressible equilibrium in cylindrical geometry.

Detailed numerical comparisons of the nonlinear solutions will be presented for the flux and current constraints appropriate to tokamaks and RFP. Most probable equilibria for tokamaks are investigated using the equations derived for $B_z(r) \geq 0$ while RFP equilibria are obtained when the model is extended to permit arbitrary $B_z(r)$.

Parallels are drawn between most probable equilibria and Taylor states. For both tokamaks and RFP's, the most probable states show a tendency toward low β equilibria as the energy-to-helicity ratio is decreased.

For the RFP, a study is made of the onset of reversal as a function of the pinch parameter Θ, and also as the energy-to-helicity ratio decreases. The pressure profile usually becomes hollow for deeply reversed equilibria.

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[1] D. Montgomery. L. Turner, and G. Vahala, J. Plasma Phys. 21, 239 (1979).

SIMULATION OF IMPURITY INJECTION INTO ISX-B*

E. C. Crume, Jr., D. E. Arnurius and R. C. Isler

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

We continue to upgrade our numerical simulation of transport of multiple species of impurities in tokamaks[1] in order to develop a calculational module treating impurity transport and impurity atomic physics for general application in tokamak transport simulation codes. For this development, we utilize a stand-alone code that treats only the impurity dynamics. This approach requires that we obtain electron density and temperature profiles, ion temperature profiles, etc., from experimental data and various models. Recently, a series of experiments has been run on ISX-B in which the gaseous impurity argon has been injected during the flat current portions of the discharge.[2] In these plasmas, the impurities are in the Pfirsch-Schlüter regime, and we have used both exact and recently developed approximate Pfirsch-Schlüter diffusion coefficients to treat impurity transport. We present here both a summary of the approximate diffusion coefficient expressions and a summary of the results of the simulation calculations.

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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] T. Amano and E. C. Crume, "Simulation of Multispecies Impurity Transport in Tokamaks," ORNL/TM-6363 (June 1978).

[2] R. C. Isler, E. C. Crume, D. E. Arnurius and L. E. Murray, "Impurity Transport During Neutral-Beam Injection in the ISX-B Tokamak," submitted to Phys. Rev. Lett.

ADIABATIC COMPRESSION AND NEUTRAL BEAM BUILDUP IN A FIELD REVERSED MIRROR CONFIGURATION

J. K. Boyd, S. P. Auerbach, H. L. Berk, B. McNamara, P. A. Willmann
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

Equilibrium methods[1] implemented in the field reversed mirror transport code[2,3] are used for adiabatic compression and neutral beam buildup of a Hills vortex equilibrium. Neutral injection scenarios related to the Beta II experiment are presented.

Problimak[4] equilibria, shown to be stable to tilting with distant walls, are demonstrated to be obtainable from a Hills vortex by adiabatic compression using external field loops. Flux from external current elements and the open boundary condition for the Grad-Shafranov equation is calculated by a Green's function technique. Numerical algorithms including the implementation of the Incomplete Cholesky Conjugate Gradient method[5] are discussed.

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

1. H. Grad, "Survey of 1-1/2D Transport Codes," Courant Institute Report MF-93, (1978).
2. D.E. Shumaker, "Field Reversed Mirror Transport Code," Bulletin Am. Phys. Soc. Vol. 24, No. 8, 1979.
3. See D.E. Shumaker, proceedings this conference.
4. See J.H. Hammer, proceedings this conference.
5. D. S. Kershaw, "The Incomplete Cholesky - Conjugate Gradient Method for the Iterative Solution of Systems of Linear Equations", J. Comp. Phys. 26 (1978) p. 43.

**Request this poster be given a position with the poster by D. Shumaker.

Abstract - 84207

2C17

FIELD-REVERSED MIRROR TRANSPORT CODE*

D.E. Shumaker

National Magnetic Fusion Energy Computer Center
Lawrence Livermore Laboratory
Livermore, California

J.K. Boyd, S.P. Auerbach, H.L. Berk, and B. McNamara

Lawrence Livermore Laboratory
Livermore, California

A code has been developed which describes the evolution of an axisymmetric field-reversed plasma. The evolution calculation consists of two alternating steps, the solution of the 1-D transport equations and the solution of the 2-D equilibrium equations. The transport equations are the flux surface averaged transport equations of Braginskii. These transport equations advance quantities which are proportional to: (1) number of particles between adjacent flux surfaces, (2) electron entropy between adjacent flux surfaces, (3) ion entropy between adjacent flux surfaces and (4) toroidal magnetic flux between adjacent flux surfaces. In the absence of collisions these are adiabatic quantities. The 2-D equilibrium calculation was developed by J.K. Boyd.[1] Results are presented for the decay of a Hill's vortex model.

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

[1] J.K. Boyd, S.P. Auerbach, H.L. Berk, B. McNamara and P.A. Willmann, this meeting

Poster session perferred.
Please place adjacent to J.K. Boyd, et al., "Adiabatic Compression and Neutral Beam Buildup in a Field-Reversed Mirror Configuration"

1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

MAGNETIC FIELD PROFILES FROM INVERSE NORMAL MODE PROBLEMS*

T. E. Cayton and D. C. Barnes
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

Measuring the magnetic field is an important and outstanding problem in the Reversed Field Z-Pinch program. The space and time dependence of plasma temperature and density are obtainable from laser interferometry and scattering techniques, but the high-β and strong shear of the Reversed Field Pinch configuration severely limit the options for magnetic field diagnostics.

Given the available measurements of density and temperature, an inverse normal mode problem for magnetoacoustic oscillations may yield the desired magnetic field profiles.

The inverse normal mode method is a spectral technique involving three steps:

1. Observation of the spectrum of the unknown problem.
2. Calculation of the spectrum of a nearby problem whose magnetic field profiles are known.
3. Inference of the unknown magnetic field profiles from differences between the observed and computed spectra.

Spectral techniques such as this have been fruitful for other mechanical and quantum mechanical systems; they rely on self-adjointness of the system being investigated.

*This work performed under the auspices of the U.S. Department of Energy.

2C19

Statistical Mechanics for the Model System of the Forward Raman Instability*

G. Schmidt, Stevens Institute of Technology
T. Tajima, University of California, Los Angeles
R. Pellat, Ecole Polytechnique

The multiple forward Raman scattering instability is important for the electron acceleration[1] and electron heating.[2] If we isolate the photon-plasmon coupling process from the wave-particle interaction, the system can be described just by mode-mode coupling equations. Properties of these equations are investigated. The three wave coupling produces a well-known periodic energy exchange in time. The four wave case is still periodic but with substructure. Systems with more than four waves seem to present chaotic patterns. If the system is chaotic and ergodic, one can construct a statistical mechanics based on a phase volume conservation and a couple of conservative quantities, creating a 2N dimensional phase space. For a simplest model we took, the expectation value for the each mode obeys equipartition. For the laser electron acceleration, the equilibriation time is longer than the acceleration time.

[1] T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979).

[2] B. I. Cohen, A. N. Kaufman, and K. M. Watson, Phys. Rev. Lett. 29, 581 (1972).

*Work partly supported by NSF and Aspen Center for Physics.

POSTER SESSION REQUESTED

2C20

Magnetic Field Curvature in Torsatrons/Stellarators.*

D. T. Anderson and J. L. Shohet

The University of Wisconsin, Madison, Wis. 53706 USA

The local magnetic field line curvature has been investigated numerically in torsatrons and stellarators. The curvature is found from local field and gradient values calculated from a Biot-Savart formulation of the fields from filamentary conductors, without using any expansions for the field structure. The curvature information has been used to determine the connection length in torsatron and stellarator type devices. The connection length is represented as the distance along the field between points of good curvature. In a tokamak, for reasonable values of q, the toroidal curvature dominates the poloidal curvature and the connection length is approximated by the distance a field line travels in moving around the minor cross-section of the device. We have applied the same criterion, i.e. curvature of the field lines convex to the plasma, for determining the connection length in torsatrons and stellarators as compared to tokamaks. To accomplish this, we take the dot product of the curvature vector with an outward directed normal from the flux surface. This gives the component of the curvature of the field in the direction of the plasma pressure. This calculation gives the same results for curvature and connection lengths if applied to a tokamak as the previously mentioned argument, while providing a working definition for application to non-axisymmetric devices.

When this method is applied to stellarators and torsatrons the curvature is modulated as the field line makes a poloidal revolution. This modulation is found to occur at field period intervals. In other words, if a field line passes once around the torus in moving from the outside to the inside and the machine has 12 field periods, the dot product of the curvature and the surface normal plotted as a function of length along the field has a cosine form for the toroidal curvature modulated by a cosine with 12 periods for $\iota = .5$. The amplitude of the modulation is dependent on the parameters ε_T and ε_H, the toroidal and helical modulation of the field respectively. If the modulation is large enough, the curvature can change from bad to good within a field period, which can be considerably shorter than the toroidal connection length. This may be beneficial in decreasing the growth rate of modes whose growth rates are dependent upon the connection length.

Comparisons will be presented between stellarators and torsatrons showing the differences the ordering of the fields make as related to the curvature calculations. In general, since in a torsatron $\varepsilon_H > \varepsilon_T$, torsatrons will have a shorter connection length than a stellarator, and stellarators will have a slight reduction in connection length as compared to a tokamak.

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2C21

Linear Theory of the Ordinary Mode Electron Cyclotron Resonance Heating in Tokamak Plasmas*

V. Arunasalam, P. C. Efthimion, J. C. Hosea, and H. Hsuan

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

Closed form expression of the optical depth τ for nearly perpendicular propagation (with respect to the toroidal magnetic field) of the ordinary mode microwave radiation near the fundamental electron-cyclotron frequency ω_c is reexamined. It is found that for finite k_z (i.e., $k_\perp > k_z \neq 0$) the absorption resonances have maximum values at $\omega \approx \omega_c \pm k_z(2\kappa T/m)^{1/2}$ and the absorption approaches zero as $\omega \to \omega_c$. As k_z approaches zero, the seperation between the two neighboring resonances at $|\omega| \approx |\omega_c| \pm k_z(2\kappa T/m)^{1/2}$ decrease and in the limit as $k_z \to 0$ merge into a single two-fold degenerate resonance at $|\omega| \approx |\omega_c|$. For a tokamak plasma ($B \alpha R^{-1}$) and for $k_z \to 0$, $\tau \simeq (\pi R \omega_p{}^2 \kappa T/2\omega mc^3)(1-\omega_p{}^2/\omega^2)^{1/2}$, where ω_p is the plasma frequency. The fractional absorbed power F in ECRH is $F \approx [1-\exp(-\tau)]$ on a single transit of the absorption region. If the wall reflection coefficient b is large, the effective value of $F \approx [1-\exp(-\tau)]/[1-b \exp(-\tau)]$, and multiple transits will enhance the ECR absorption considerably.

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

1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

ROTATION OF A FIELD REVERSED THETA PINCH*

D. C. Barnes and C. E. Seyler
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

Compact tori produced in field reversed theta-pinch experiments (FRX)[1] often exhibit rotational fluid instabilities. Indirect experimental evidence suggests that the FRX is formed with negligible rotation and then accelerates until, rotating rigidly, the instability threshold is attained and the plasma rapidly disrupted. The observed rotational mode is consistent with theory predicting instability for $\alpha = -\Omega/\Omega_* \gtrsim 1.5$, where Ω is the rigid rotation frequency and Ω_* the ion diamagnetic drift frequency.[2]

The above observations are explained by rapid particle loss from FRX. It is assumed: 1) The plasma is described by a very elongated, charge neutral, rigid rotor equilibrium; 2) The plasma radial profile changes negligibly in time; and 3) The resistive diffusion time is long compared to the particle confinement time. Using conservation of angular momentum between t and t+dt

$$\frac{d}{dt}\,[(1-F)\alpha] = \left(2 + \frac{\Delta}{(1-\Delta)^{1/2}} - \frac{1}{4\lambda} - 2\alpha\right)\frac{dF}{dt}$$

where Δ is the plasma β at the separatrix, $\mathrm{sech}^2\,\lambda = \Delta$, and F is the fraction of plasma lost at time t. Integrating the above, $\alpha = F\left(2 + \frac{\Delta}{(1-\Delta)^{1/2}} - \frac{1}{4\lambda}\right)$. For FRX-B, F = .55 at $\alpha = 1.5$. This may be compared to an experimentally observed inventory of F = .54 at the time instability is observed.

It follows from the above that rotational instability occurs only after most of the plasma is lost. Thus, instability will be avoided when the particle confinement is improved. Equilibrium considerations suggest two approaches for improving confinement: 1) Reduce the plasma radial compression; 2) Reduce the open field line loss rate. Both of these are being pursed experimentally.

*This work performed under the auspices of the U.S. Department of Energy.

1. W. T. Armstrong, et. al., "Field Reversed Experiments (FRX) on Compact Tori", submitted to Phys. Fluids for publication.

2. C. E. Seyler, Phys. Fluids, 22, 2324 (1979).

2C23

Absorbtion of Wave Momentum by Trapped Electrons*

N. J. Fisch
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

Current generation in tokamaks by means of unidirectional traveling Alfvén waves has been suggested as a means for continuously maintaining the poloidal magnetic field.[1] Previous calculations[2] of the current generated and power dissipated by this means ignored the effects of trapped electrons. There is strong motivation to examine these effects since the favorable regime of operation occurs when the wave momentum is absorbed by low-$v_{\|}$ high-$v_{\perp}$ electrons, which are precisely the trapped electrons in a tokamak. The trapped electrons cannot directly convert the momentum absorbed into current; instead they experience a radial drift toward the magnetic axis. This drift is similar to the Ware pinch effect, but there are important differences too. The pinch here occurs diffusively; there is no tilting of the banana orbit, instead the inside orbit of the banana diffuses towards tha magnetic axis while the outside orbit remains fixed. Furthermore, in contrast to a dc electric field, the waves act only on the trapped electrons. The circulating electrons are affected by collisions and the ions respond both to collisions and a self-consistent radial potential. The distribution functions may be found by the usual neoclassical matching techniques.[4].

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

[1] D.J.H. Wort, Plasma Physics 13, 258 (1971).

[2] N.J. Fisch and C.F.F. Karney, PPPL-1624 (1979).

[3] A.A. Ware, Phys. Rev. Lett. 25, 916 (1970).

[4] P.H. Rutherford, L.M. Korvizhnikh, M.N. Rosenbluth and F.L. Hinton, Phys. Rev. Lett., 25, 1090 (1970).

2C24

Integral Method for Solving Tokamak Equilibria*

T. Mizuguchi and T. Kammash
University of Michigan

D. J. Sigmar and H. K. Meir
Oak Ridge National Laboratory

We have obtained tokamak equilibria by solving the integral forms of the equilibrium conditions instead of solving the non-linear elliptical differential equation. With the appropriate Fourier representation of coordinates we justify the following form of inverse equilibrium i.e.,

$$X(\psi,\chi) = X_c + \delta(\psi) + \sqrt{\psi}\,(\xi_0 + \xi_1\psi)\cos\chi$$

$$Z(\psi,\chi) = (E_0 + E_1\psi)\left\{\sqrt{\psi}\,(\xi_0 + \xi_1\psi)\sin\chi - \psi(\nu_0 + \nu_1\psi)\sin 2\chi\right\}$$

on the basis of ISX equilibrium data. The eight coefficients in this representation are obtained from four boundary conditions, the virial theorem, the pressure balance, and the dipole and quadrupole moments.(1) For the standard approximation in which the deformations of flux surfaces near the magnetic axis are of order ε, terms representing these derivations vary linearly with the pressure. Because of large flux surface changes in the finite beta case the magnitude of the Shafranov shift , elliptical deformation, and the perturbation in the minor radius become comparable in this analysis. The dipole and quadrupole moments are examined for various plasma cross sections, and the resulting equilibrium model is shown to have special advantages in the optimization of the plasma cross section for high beta systems.

(1) L. E. Zakharov and J. D. Shafranov, Sov. Phys. Tech. Phys. 18, 151 (1973).

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*Work supported by U.S. DOE

LBL-10600 Abs.

INTERPRETATION OF THE COLLISIONLESS DRIFT MODE IN A SHEARED MAGNETIC FIELD*

Celso Grebogi and Russell M. Kulsrud+

Lawrence Berkeley Laboratory, University of California,
Berkeley, California 94720

Alternatives to the complex plane WKBJ methods for solving the differential equation for drift waves in a sheared magnetic field are considered. This work explores such alternatives, and isolates part of the problem in order to identify the causes of stability and/or instability of the drift mode. Asymptotically the problem is broken into three regions: (i) an outer region where only the ion terms contribute; (ii) an intermediate region where both ion and electron dynamics are important; and (iii) an inner region, the electron layer, that is governed by the electron dynamics. We transform the intermediate region into a reflection problem by an appropriate boundary condition at the inner layer. To study the intermediate region the problem is reduced to that of Pearlstein and Berk by dropping the real part of the electron Z-function. The resulting differential equation is solved using transform techniques, and the dispersion relation is reduced to an integral that can be approximated by the steepest descent method. For the case of reflecting boundary on the inner side of the intermediate region we find instability. This result would support the conclusion that stabilization of the drift mode is produced by the electron dynamics in the inner layer.

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+Permanemt address: Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544.

2C26

ORAL SESSION

BETA OPTIMIZATION OF NON-CIRCULAR TOKAMAK EQUILIBRIA TO IDEAL MHD MODES

R. W. Moore, L. C. Bernard, F. J. Helton, and R. L. Miller

General Atomic Company
San Diego, California 92138

ABSTRACT

Results are presented of an automated search for the current profile and equilibrium shape which gives the maximum stable beta for equilibria which can be generated by a practical, discrete set of field-shaping coils. Both dee shapes and doublets are examined. The poloidal beta and current profile are varied by changing parameters controlling the pressure and toroidal current profile half widths. The shape is varied by changing the poloidal flux on the field-shaping coils. We find optimal shapes which are stable to both internal ballooning modes (BLOON[1] code), and internal and external kink modes (GATO[2] code). We find $\beta > 6\%$ for both dees and doublets. Both shapes attain maximum stable beta with current profiles that are much broader than standard ohmic heating profiles, suggesting that current profile control is needed to achieve these beta limits.

Work supported by Department of Energy, Contract DE-AT03-76ET51011, GA Project No. 3235.

[1] R. Miller and R. Moore, Phys. Rev. Lett. *43*, 765 (1979).

[2] R. Moore, *et al.*, Bull. Amer. Phys. Soc. *659*, Vol. 24 No. 8 (1979).

Nonlinear Propagation and Coupling of Lower Hybrid Waves Excited by a Waveguide Array

K. Theilhaber, K. Ko, V. Krapchev and A. Bers
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

In the vicinity of a waveguide array radiating into a tokamak plasma, high power densities and low temperatures lead to strong ponderomotive density modulation both perpendicular and parallel to the magnetic field. We solve the self-modulated Maxwell equations [1] numerically for a two-dimensional homogeneous plasma, in a model which retains electromagnetic effects but neglects thermal dispersion. The nonlinearity is of the "static" form, $\exp(-e^2|E|^2/m\omega^2T)$. Our formulation is valid in the edge region, up to the waveguide apertures, in contrast to the CMKdV equation [2] which is valid only once lower hybrid cones have separated. Also, the effect of finite extent in z is included, in contrast to previous treatments with an infinite travelling-wave excitation [3]. We examine the nonlinear spectrum and nonlinear reflection of waves radiating from an imposed source. Extension to the fully self-consistent waveguide coupling problem is outlined.

[1] K. Theilhaber, K. Ko, V. Krapchev and A. Bers, *Bull. Am. Phys. Soc.*, 24, 1019 (1979).

[2] C. F. F. Karney, A. Sen and F. Y. F. Chu, *Phys. Fluids*, 22, 940 (1979).

[3] V. S. Chan, S. C. Chiu, *Phys. Fluids*, 22, 1724 (1979).

*Work supported by DOE Contract ET78-S-02-4682.

SELF-CONSISTENT VLASOV DESCRIPTION OF THE FREE ELECTRON LASER INSTABILITY IN A RELATIVISTIC ELECTRON BEAM WITH UNIFORM DENSITY†

Ronald C. Davidson
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Mass. 02139

Han S. Uhm
Naval Surface Weapons Center
White Oak, Silver Spring, MD 20910

The development of advanced millimeter and submillimeter radiation sources for high-frequency plasma heating is a subject of considerable importance to the fusion program. In this paper, a self-consistent description of the free electron laser instability is developed for a relativistic electron beam with uniform density propagating through a helical wiggler field $\underset{\sim}{B}^0 = -\hat{B} \cos k_0 z \hat{\underset{\sim}{e}}_x - \hat{B} \sin k_0 z \hat{\underset{\sim}{e}}_y$. The analysis is carried out for the class of solutions to the Vlasov-Maxwell equations described by $f_b(z,\underset{\sim}{p},t) = n_0 \delta(P_x) \delta(P_y) G(z,p_z,t)$ where P_x and P_y are the exact canonical momenta invariants perpendicular to the beam propagation direction. The linearized Vlasov-Maxwell equations lead to an exact matrix dispersion relation which is valid for perturbations about general beam equilibrium $G_0(p_z)$ and includes coupling to arbitrary harmonic number (n) of the fundamental wiggler wavenumber k_0. No a priori restriction is made to low beam density (as measured by $\omega_p^2/c^2k_0^2$) or small wiggler amplitude (as measured by $\hat{\omega}_c/ck_0 = e\hat{B}/\bar{\gamma}mc^2k_0$). Moreover, no assumption is made that any off-diagonal elements in the matrix dispersion relation are negligibly small. A detailed numerical analysis of the exact dispersion relation is presented for the case of a cold electron beam described by $G_0(p_z) = \delta(p_z - p_0)$. It is shown that the instability bandwidth increases rapidly with increasing wiggler amplitude $\hat{\omega}_c/ck_0$. Moreover, except for very modest values of wiggler amplitude, it is shown that the growth rate calculated from an approximate version of the dispersion relation can be in substantial error for large values of $(k + nk_0)/k_0$. Preliminary estimates of the influence of beam thermal effects are also presented.

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† Research supported by the Office of Naval Research

Abstract for 1980 Sherwood Meeting, Theoretical Aspects of Controlled Thermonuclear Research, Tucson, Arizona, April 23-25, 1980:

Feasibility and Credibility of a Three-Dimensional Relativistic Electromagnetic Particle Code Based on a $2*128^3$ Grid

O. Buneman, Stanford University

Powerful electrostatic and/or lower-than-three-dimensional particle codes exist and are contributing credible information toward the understanding of plasmas. Experiments with a fully 3-d, relativistic e-m code over a 32^3 grid have given interesting answers, but the low resolution, plus the high noise level, cause one to accept these answers only with reservations. We have explored the limits to which presently available computer power (meaning the MFECC's CRAY-1 with its time-sharing environment) allows one to improve such a code. The result is a scheme in which a cubic-centered grid with $2*128^3$ data points is used as a base for tetrahedral interpolation and in which some 3 million particles and their fields can be updated through one time step in about one minute: Data management rather than computation is the major difficulty. In order to get useful results in reasonable times, it is still necessary to practice compression of significant ratios, such as m_i/m_e , L/λ_D , c/v etc., but we have evidence that at least qualitatively acceptable answers will result from such a code.

2C30

1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

AC CONDUCTIVITY IN A HOMOGENEOUS PLASMA FROM A CONVERGENT COLLISION INTEGRAL*

R. L. Guernsey
University of Maryland, College Park, Maryland 20742
and
J. P. Mondt
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

From the fundamental physics point of view the microscopic foundations of the theory of plasma transport still constitute an outstanding problem, even in the "simple" and rare case of a quiescent plasma. In a recent article[1] some of the inconsistencies and unnecessary assumptions made in arriving at a convergent collision integral were removed.

The purpose of this work is to report on the derivation of the high-frequency ($\nu_{e,i} < \omega << \omega_{pe}$) electrical conductivity obtained from this integral. The result is given in terms of an expansion in the plasma parameter and its logarithm and is compared with previously obtained results.

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

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2C31

THE EFFECT OF SCATTERING BY DENSITY FLUCTUATIONS ON THE ACCESSIBILITY OF LOWER HYBRID WAVES*

Paul T. Bonoli and Edward Ott
Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20742

An understanding of the accessibility of lower hybrid waves is a fundamental prerequisite for design of a heating experiment. Recent observations on Alcator A are in gross disagreement with the simple theory. The work reported here shows that it is essential to include other realistic effects (particularly density fluctuations and toricity) to explain these results and to predict behavior in other devices as well. The formulation of the problem proceeds via a wave kinetic equation with scattering of the lower hybrid waves by density fluctuations in toroidal geometry. The determination of accessibility involves a proper treatment of wave scattering in the regime where electromagnetic effects are important (such as the scattering of the slow wave into the fast wave and vice versa). Numerical solutions of the wave kinetic equation with scattering are obtained using a Monte Carlo technique that treats both large and small angle wave-wave collisions.

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

TOROIDAL ROTATION EFFECTS IN BEAM-HEATED TOKAMAKS*

W. A. Cooper and J. T. Hogan

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

High power unidirectional neutral beam injection should produce a large toroidal rotation velocity, which could alter the ballooning stability boundaries. To explore this question with regard to recent ISX-B experiments (with $P_{inj} \lesssim 1MW)^1$, we have coupled together models for the following processes:

a) Momentum deposition, calculated both with a 2D $(V_\perp V_\parallel)$ Fokker-Planck code[2] and with a moments approximation.

b) $1\frac{1}{2}$D transport, with the rotational pressure contributions included in the Grad-Shafranov equation.

c) High-n ballooning stability, using both the Bateman model[3] and an analytic criterion derived by Pogutse-Yurchenko[4].

In the undamped case (i.e., $mn\dot{U}_\parallel = K_{beam}$) we find that the toroidal rotation speed does not build up to have a significant effect on either the equilibrium or stability calculation until after $\beta > \beta_{crit}$. It is possible that even small V_ϕ could change the criteria used in c), and extensions of the high-n theory for $V_\phi \neq 0$ are under investigation.

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

[1] D. Swain et al, Proc. 9th Europ-Conf. on Pl. Phy. and CTR, Oxford, 1979.

[2] R. H. Fowler et al., Comput. Phys. Commun. 13 (1977) 323.

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[4] O. P. Pogutse, E. Yurchenko, Fizika Plazmii, 5 (1979) 786.

2C33

The Second Region of Stability*

John M. Greene and Morrell S. Chance
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

An improved model will be shown that yields the second region of stability[1] with respect to ballooning modes. This phenomenon depends on large pressure gradients, but not directly on large values of the pressure itself. Furthermore, large toroidal mode number ballooning instability depends only on equilibrium parameters local to a given surface. It is thus reasonable to consider local perturbations that negligibly affect the magnitude of the pressure and safety factor but produce significant variations in their gradients. The equilibrium variations induced by such perturbations can be evaluated in terms of integrals over unpertrubed equilibrium quantities, and the result inserted in the coefficients of the standard ballooning mode equation. These are affected by the perturbation only through variations in the pressure gradient and the local shear.[2] Computations have been performed on an accurately determined numerically evaluated equilibrium with a moderate pressure. The ballooning instabilities tend to be localized near points where the local shear vanishes, and to a rough approximation, exists only when the normal curvature is unfavorable at these points.

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*Work supported by U. S. DoE Contract DE-AC02-76-CH03073.

1. B. Coppi et al., Comments on Plasma Physics 5, 1 (1979); H. R. Strauss et al., to be published in Nuclear Fusion; see these for other references.

2. J. M. Greene and J. L. Johnson, Plasma Physics 10, 729 (1968).

2C34

On the MHD Continuous Spectrum in General Toroidal Geometry

J.A. Tataronis
Courant Institute of Mathematical Sciences
New York University

Abstract

The existence of a continuous spectrum of the linearized ideal MHD equations has been established for equilibria possessing sufficient spatial symmetry, in particular for the planar sheet pinch[1], the cylindrical screw pinch[2], and for axisymmetric toroidal geometry[3]. The continuum can be characterized by an eigenvalue problem consisting of algebraic equations for the sheet and screw pinches, and an ordinary differential equation over a finite domain for axisymmetric toroidal equilibria. However, in the general toroidal case, where no spatial symmetry exists, the mathematical problems that arise are much more complicated. The continuum is characterized by a fourth order system of ordinary differential equations along the equilibrium magnetic field lines. The appropriate boundary conditions are discussed, and the existence or non-existence of solutions of the system on both rational and irrational magnetic surfaces is considered. The implications of the results to possible plasma heating arising from spatial singularities is commented on.

Work carried out under DOE Contract #DE-AC02-76ER03077

1. J.A. Tataronis and W. Grossmann, Z Physick, 261, 203 (1973)
2. J.A. Tataronis and W. Grossmann, Nucl. Fusion 16, 667, (1978)
3. Y.P. Pao, Nucl. Fusion 15, 631, (1975)

EFFECTS OF FAST-WAVE HEATING ON EBT ION TRANSPORT*

R. B. Campbell**, R. J. Kashuba, and T. Kammash**
McDonnell Douglas Corporation
St. Louis, Missouri 63166

We present analytic expressions for EBT neoclassical transport coefficients for ions in the plateau regime of collisionality, including the effects of fast-wave heating. We focus our attention on two separate cases: heating at frequencies near (1) the fundamental and (2) the second harmonic of the cyclotron frequency of the single ion species.

The transport coefficients obtained can be either smaller or larger than the coefficients without wave heating, depending on the value of the normalized ambipolar potential. This result may be interpreted as the effect of particles being scattered by waves either away from or into the region in velocity space where the poloidal drift frequency vanishes.

Since scattering of intermediate energy particles by waves is more pronounced for second harmonic heating, the impact on transport coefficients is greater, up to a factor of three enhancement, in this case.

The coefficients have been incorporated into a point model, and power balance solutions will be presented using the modified coefficients. Results indicate that if the density gradient scale length is treated as a parameter, one of the major wave-heating effects observed is that the ion heating tends to increase the potential gradient where the density gradients are steep. This effect could be observable in an ion-heated experiment, particularly if some degree of edge heating by waves exists.

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**Permanent Address: University of Michigan, Ann Arbor, Michigan 48109

2C36

SKELETOMAK - High β Tokamak with a MHD "Rigid" Spinal Column[*]

P. Kaw, W. Park, and E. Valeo
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

It is argued that if q(0) in a tokamak plasma can be depressed significantly below 1, without incurring the wrath of violent MHD/resistive internal kink modes, then its high β stability performance will be improved because of a shortened connection length and increased shear. Extending Taylor's $\int_V B \cdot A d\tau$ = constant and free energy minimization argument, it is shown that introduction of a "rigid" spinal column carrying a significant fraction of tokamak current, produces MHD/resistive stable tokamak-like q profiles but with $q(0) << 1$. Treating the spinal column as a rigid current, we show by explicit calculation that the plasma is stable to $m = 1$ kink-tearing as well as to MHD ballooning modes for a β_{peak} as high as 75%. All this assumes that the spinal column itself is stable even though its q is less than 1. We examine the possibility that a relativistic particle beam (externally introduced or produced internally by runaway effects) be used to replace the spinal column. Some results of the MHD/resistive stability of such beams with q(0) below 1 will be presented.

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2C37

Spectral Estimates, Stability Conditions and the Rotating Screw Pinch

E. Hameiri

Courant Institute of Mathematical Sciences

New York University

Abstract

We present two sufficient conditions for the stability of rotating plasmas, the first based on conservation of circulation and the second based on circle theorems applicable to Hamiltonian systems. The circle theorems also provide bounds on eigenvalues in the complex plane. All results are applied to the rotating screw pinch which can be described by a single, second order, ordinary differential equation. We show how the introduction of two additional parameters into the equations can be used by any numerical code to compute bounds on the unstable spectrum and to restrict the search to a fixed domain in the complex plane, regardless of how large the wave numbers are.

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poster session

2C38

Diffusion of Charged Fusion Reaction Products by Transient Magnetic Fluctuations

F. Pegoraro[+] and B. Coppi
Massachusetts Institute of Technology

A thermonuclear experiment can reach ignition when the "economy" of fusion products is such that their local heating rate compensates for all thermal losses. A key factor in this "economy" is the possible excitation of magnetic fluctuations that could deteriorate the confinement of fusion products.

We refer to a sheared axisymmetric magnetic configuration and consider perturbations that arise from a mixing of shear-Alfvén waves with interchange modes. Then different experiments can be distinguished on the basis of a parameter that characterizes the influence of the plasma kinetic pressure relative to that of the magnetic field, and that is related to the excitation of the so called ballooning instability. In fact it has been shown[1] that when the ballooning instability region is approached either from the first or from the second[2] stability region, fusion products can enhance the magnetic fluctuation level through a resonant interaction. A central feature is that the relevant fluctuations cannot be described in terms of eigen-modes. The phenomena that occurs in the vicinity of the ballooning instability region has led us to describe them as "opalescent" fluctuations. Such opalescence is mostly marked in the second stability region where a "quasi-discrete" spectrum can be found, as is characteristic of quantum mechanical systems[3] that can disintegrate, with enhanced distortion and time delay of the incident wave-packets.

Then an important question we have addressed is whether these oscillations effectively diffuse the fusion products, or whether their transient nature limits the quasi-linear diffusion process that would be expected in the case of normal modes.

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[+] Scuola Normale Superiore 56100 Pisa, Italy.

2C39

THE PROBLIMAK: A NON-TILTING FIELD-REVERSED EQUILIBRIUM

James H. Hammer
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

The tilting instability has been predicted to be a severe constraint on field reversed equilibria, requiring an oblate shape with a close fitting conducting shell for stability[1] $(r_{\mathrm{wall}}/r_{\mathrm{plasma}} - 1 \overset{\sim}{<} .2|\varepsilon|$; ε = (axial length)/(radial length) - 1). It is now shown by extension of the Rosenbluth-Bussac analysis that some prolate plasmas can be stable to tilting with walls quite distant from the plasma surface $(r_{\mathrm{wall}}/r_{\mathrm{plasma}} - 1 \overset{\sim}{<} 50\ \varepsilon)$. The new feature of these equilibria is the non-elliptical character of the plasma boundary, which has an equatorial bulge on an otherwise prolate shape. Since the shape has elements of both the prolomak and the oblimak, it is dubbed the problimak. The stability of the problimak to axial and transverse displacements has also been investigated, with the result that it is found to be stable against the axial mode and easily wall stabilized against the transverse mode. An analytic problimak equilibrium with its corresponding array of external currents will also be presented.

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1. M. N. Rosenbluth and M. N. Bussac, Nucl. Fusion, 19 (1979) 489-498.

POSTER SESSION

2C40

LBL-10727

STOCHASTIC PROPERTIES OF THE CHIRIKOV-TAYLOR MAPPING*

Henry D. I. Abarbanel, Celso Grebogi, Allan N. Kaufman

Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720

The "standard" mapping

$$\begin{aligned} I_{n+1} &= I_n + (k/2\pi)\sin 2\pi\theta_n \\ \theta_{n+1} &= \theta_n + I_{n+1} \end{aligned} \qquad \text{(mod 1)}$$

arises in many problems in plasma dynamics. We have studied the statistical properties of a single orbit, for various values of the parameter $k > 4$, i.e., well within the stochastic domain. For most tests, we <u>code</u> the orbit by coarse-graining I-space into 10 equal cells, and expressing the orbit as a "semi-infinite" sequence of ($N > 10^4$) digits, e.g. 8, 1, 4, 4, 7, 9, 7, 8, 7, 2, 2, 3, 5, 5, 1, 5, 5, 3, 2,... We then examine various joint and conditional probabilities, by counting the relative frequency of finite sequences. For example, P(3,5) is the relative frequency of the 2-digit sequence 3,5.

First we test for ergodicity by comparing P(a) for all a = 0,1...9; we find them all equal (to within expected fluctuations), demonstrating essential ergodicity, for $k > 4$. Next we test for statistical independence of I-values m iterations apart, and find it for $m \geq 8$ at $k = 5$, for $m \geq 6$ at $k = 7.5$, for $m \geq 1$ at $k = 50$. A related test is for the Markov amnesia time m_A: for $m \geq m_A$, the conditional probabilities obeys the Markov assumption for the mth iterate of the mapping. We find that $m_A = 5$ for $k = 7.5$. Under Markov and non-Markov conditions, we evaluate the transition matrix $P(b|a)$ and its associated entropy. We relate the latter to the Kolmogorov-Sinai entropy and to the Lyapunov exponent. Finally, without coarse-graining, we evaluate the autocorrelation function $\langle \exp 2\pi i(I_{n+m} - I_n)\rangle$ as a function of discrete m and continuous k.

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2C41

Chaotic (Strange) and Periodic Behavior in Instability Saturation by the Oscillating Two-Stream Instability*

D. Russell,[a] E. Ott,[b] and J. M. Wersinger[c]

We study a simple model of nonlinear saturation of a linearly unstable wave. The nonlinear Schroedinger equation with linear growth and damping is truncated to three waves. The resulting system of nonlinear, first order, ordinary differential equations describes the excitation of linearly damped waves by the oscillating two-stream instability driven by a linearly unstable pump wave. As the dimensionless parameters of this system are varied, the model exhibits a wide variety of characteristic dynamical behavior. This behavior includes stationary equilibria, Hopf bifurcations to periodic orbits, period doubling bifurcations, chaotic behavior, transient chaos, and hysteresis. We explain most of these phenomena using one-dimensional maps derived from the Poincaré map for this system and give evidence for the existence of a strange attractor in the chaotic regime by demonstrating scale invariance in the Poincaré map.

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

Addresses: a) Cornell University; b) University of Maryland; and
c) Auburn University.

2C42

POSTER SESSION

ON THE PLASMA DISPERSION RELATION NEAR THE TWO-ION HYBRID RESONANCE

S. C. Chiu, V. S. Chan, and J. Y. Hsu

General Atomic Company
San Diego, California 92138

ABSTRACT

Auxiliary heating of tokamak plasmas near the ion cyclotron range of frequencies is of much interest. The importance of the presence of small amounts of minority ions was realized after the earlier experiments in ATC and TFR, and the control of heating by variation of minority concentration has been demonstrated in recent experiments in TFR and PLT. In the present work, we made a detailed numerical study of the two-species plasma relation close to the ion-hybrid resonance. Within limits of parameter space of experimental interest, we found differences from previous theoretical studies. We present an approximate analytical theory that accounts for these differences. We shall discuss their implications on coupling and heating mechanisms.

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CLASSICAL TRANSVERSE TRANSPORT PROCESSES IN A STRONG MAGNETIC FIELD*

Yu Ping Ho
Institute for Advanced Study, Princeton, New Jersey 08540

ABSTRACT

We have reinvestigated the classical transport processes in a strong magnetic field. It is found that both the previous quantum theory and the classical theory (Boltzmann equation with Lorentz force term) only have zero transport solutions when we consider all the previously neglected higher order terms in gyro-orbit representation. Using the general theory of non-equilibrium statistical mechanics and projection operator technique, we introduce a macroscopic current operator and then obtain a satisfactory theory. We also explain why many previous concrete results still can be used.

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On the Mercier Criterion in Guiding Centre Theory*

A. Salat
Max-Planck-Institut für Plasmaphysik
D-8046 Garching

Abstract

Collisionless two-fluid guiding centre equations are used to investigate stability of toroidal plasma equilibria with respect to localized MERCIER-type modes. The anisotropic equilibria are characterized by $\sigma(V,B) = 1-(P_{\parallel} - P_{\perp})/B^2$, where V is the volume inside the flux surfaces. It is found that, in general, no localized MERCIER-type eigenmodes exist. For $\sigma = \sigma(B)$ such modes exist but no explicit stability condition can be given. For σ = const in the localization region and no trapped particles the necessary stability condition for axisymmetric equilibria agrees with the MERCIER criterion except that the pressure is replaced by $(P_{\parallel} + P_{\perp})/(2\sigma)$.

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2C45

Long Time Equilibrium in a Cylinder

Pung Nien Hu
Courant Institute of Mathematical Sciences
New York University

Abstract

As transport processes become important in fusion experiments, it is logical to ask the question whether the plasma will eventually reach an equilibrium after a long time. Based on Braginskii's equations which include all the dissipative mechanisms, an analytical study is made for a cylindrical plasma with Ohmic heating in the Tokamak parameter range.

Assuming similar profiles for the electron and ion temperatures (T_-/T_+ = constant), it is found that the pressure is governed by the well-known Lane-Emden equation for the structure of a polytropic gaseous star in its own gravitational field. For $T_-/T_+ > 2$, the plasma can be contained within a finite radius with a free boundary. For $T_-/T_+ < 2$, the density profile is inverted, resulting in a lower density at the center. This result may indicate the limitation to the choice of heating processes.

poster session

STEADY STATE FIELD-REVERSED EQUILIBRIA WITH APPLIED QUADRUPOLE FIELDS

H. L. Berk and James H. Hammer
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

We present here a theory of steady state operation for a beam driven, slightly asymmetric field-reversed configuration. The crucial ingredient of the theory is a magnetic pumping effect that exerts a torque on the electrons in the presence of asymmetry (e.g., external quadrupole fields). The torque prevents cancellation of the beam-produced ion current by countering the electron-ion drag force which usually accelerates electrons to the ion velocity and causes current annihilation. The steady state particle loss rate resulting from this method approaches the classical cross-field diffusion loss rate.

An additional benefit of the scheme is that the symmetry breaking quadrupole fields are excluded from the bulk of the plasma by the beam-driven toroidal mass flow, and hence do not degrade the confinement by opening up the field lines. The theory is applied to existing and planned mirror experiments (Beta II, MFTF) which conveniently have quadrupole fields and neutral beam sources of the necessary characteristics to test the scheme. Possibilities for using this method for start-up will also be discussed.

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1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

NUMERICAL SIMULATION OF m = 0 PHENOMENA IN FIELD REVERSED CONFIGURATIONS USING A TWO AND ONE-HALF DIMENSIONAL HYBRID CODE*

D. W. Hewett
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

A zero electron inertia hybrid code (PIC ions-fluid electrons) in r-z geometry[1] has been used to study m = 0 phenomena, which occur during the formation of long Field Reversed Theta Pinch (FRTP) configurations as well as the nonlinear behavior of the m = 0 resistive MHD modes in Reversed Field Z-Pinches (RFZP). Following the implosion that initiates the formation of an FRTP, a spontaneous development of short wavelength structure in the axial direction is observed. This structure is most likely initiated by an instability driven by the large temperature anisotropy produced by the implosion. The m = 0 resistive tearing mode grows far too slowly to account for this behavior. Nonlinear effects quickly cause these short wavelength modes to coalesce into closed field regions with increasing axial dimension. This process terminates, perhaps due to numerical restrictions, with one gross mode in the simulation region. Similar effects have been observed[2] in simulations of highly anisotropic equilibria.

RFZP equilibrium are generally formed on a much longer time scale than the FRTP. As a consequence of its slow formation, the RFZP has a relatively isotropic distribution of ion velocities and is, therefore, not susceptible to relatively fast kinetic instabilities. Resistive MHD modes do occur, however, and a particularly dangerous mode is the m = 0 tearing mode, which appears not to saturate at small amplitudes.[3] Simulations of this mode have been accomplished by initializing with a perturbed RFZP equilibrium. Preliminary results indicate that the FLR effects inherent in the PIC ions do not stabilize the mode.

*This work was performed under the auspices of the U.S. Department of Energy.

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3. D. Schnack, private communication.

THE PHYSICS BASIS FOR EBT-P

C. L. Hedrick
Oak Ridge National Laboratory, Oak Ridge, Tennessee

EBT-P is the next torus in the sequence leading from the present torus (EBT-I/S) to an EBT reactor. Here we discuss the theoretical basis for projecting the performance of EBT-P and the issues to be addressed by the associated experimental and theoretical research programs. One goal of the EBT-P program is to increase plasma density, temperatures, and life times to roughly the geometric mean of that already achieved and that required for a reactor. While representing a significant increase in density, temperatures, and life time, many of the dimensionless parameters are already in the EBT reactor regime. Another major goal of the EBT-P program is to test and understand beta limits more fully. EBT-P has been designed to permit simultaneously testing of beta limits while maintaining other dimensionless parameters such as collisionality. This design goal leads to higher magnetic field strength, B, in EBT-P than in EBT-I/S. Another constraint leading to higher B is the restriction imposed by microwave cutoff ($n \leq n_{crit} \sim B^2$). To separate plasma physics more fully from atomic physics (plasma/wall interaction) a larger minor radius than in EBT-I/S is necessary. Larger minor radius is also required at the higher magnetic fields of EBT-P to keep direct particle losses sub-dominant. In EBT-I/S the losses are then dominated by neoclassical electron diffusion which leads to $n\tau \sim A^2 T_e^{3/2}$ where A is the aspect ratio. This dominant loss mechanism, when coupled to power constraints, necessitates a larger aspect ratio (major radius). A wide variety of heat and particle deposition techniques as well as magnetic field shaping are contemplated for later phases of the EBT-P experiment. The aim of these improvements is to provide more independent control over the various magnetic and plasma parameter profiles. This in turn reflects the fact that stability (beta limits) is fundamentally a functional of the plasma equilibrium. Theoretical preparation for these later phases requires interactive research in magnetics, orbits, transport, stability and heating.

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NON-LOCAL STABILITY ANALYSIS OF EBT PLASMA*

J. W. Van Dam, Y. C. Lee,†
and
M. N. Rosenbluth
The Institute for Advanced Study, Princeton, New Jersey 08540

ABSTRACT

The importance of coupling the hot electron ring dynamics to the low-frequency stability behavior of the toroidal core plasma in EBT has been noticed in a local analysis.[1] There it was found that interchange stability due to the self-field well of the ring would be lost if the core pressure exceeded a relatively low threshold.

Subsequently, a more general treatment has been developed which includes non-local plasma effects in a bumpy toroidal magnetic field. An energy principle, similar to that of Kruskal and Oberman[2] but extended to include the non-MHD ring response, shows that when the plasma is stable against interchange, there still remains a strong electromagnetic mirror instability, even with nominal core pressure. Hot electron gyroradius, space charge, time delay, and other effects obtained from a drift kinetic equation are found to contribute to suppressing this instability. This may possibly be relevant to the experimentally observed T-M transition.

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†Also Department of Physics & Astronomy, University of Maryland, College Park, Maryland 20742

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THEORY OF SPHEROMAK EQUILIBRIUM AND STABILITY

— MINIMUM ENERGY STATE FOR A FINITE CYLINDRICAL PLASMA*

Z. G. An, A. Bondeson, H. H. Chen, Y. C. Lee,
C. S. Liu, G. Marklin, and E. Ott
Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20742

J. Finn and W. Manheimer
Naval Research Laboratory

The well-known Woltjer-Taylor variational principle predicts that a plasma would relax to a minimum energy state satisfying the force-free equation

$$\nabla \times \vec{B} + \alpha \vec{B} = 0 \tag{1}$$

and the conducting wall boundary condition, $\vec{B} \cdot \hat{n} = 0$ on the surface.

In a finite cylinder with radius R and length L, the conventional procedure of separation of variables implies that the only solutions of Eq. (1) subject to the conducting wall boundary conditions are axisymmetric (m=0). On the other hand, our numerical time dependent MHD calculation shows that the axisymmetric state of lowest eigenvalue α_{minimum} is unstable to m=1 perturbations when the aspect ratio L/R exceeds 1.68.

This intriguing paradox prompts a reinvestigation of the basic approach. Rather than solving (1), we minimize $\int \vec{B}^2 \, dV$ subject to $\int \vec{A} \cdot \vec{B} \, dV$ = const. using a normal mode expansion. The resulting critical value of L/R agrees with that obtained from the MHD code.

Additional results from comprehensive numerical studies of MHD and resistive spheromak stability will also be presented. One such result is the appearance of a rapidly growing kink mode when q=1 first appear in the plasma.

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Two-Dimensional Modeling of the Formation of Spheromak Configurations*

S. C. Jardin, W. Park, and M. Okabayashi
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

A reduced set of two-dimensional MHD equations have been derived describing the axisymmetric time evolution of a MHD stable plasma evolving slowly due to resistive diffusion and changing boundary conditions. The equations are restricted to low β but allow changing topology. They are integrated in time to demonstrate two possible spheromak formation methods, one of which uses "pinching coils." External circuit equations are integrated simultaneously with the plasma equations to determine the electromagnetic boundary conditions self consistently. The effects of a finite conductivity vacuum chamber are included.

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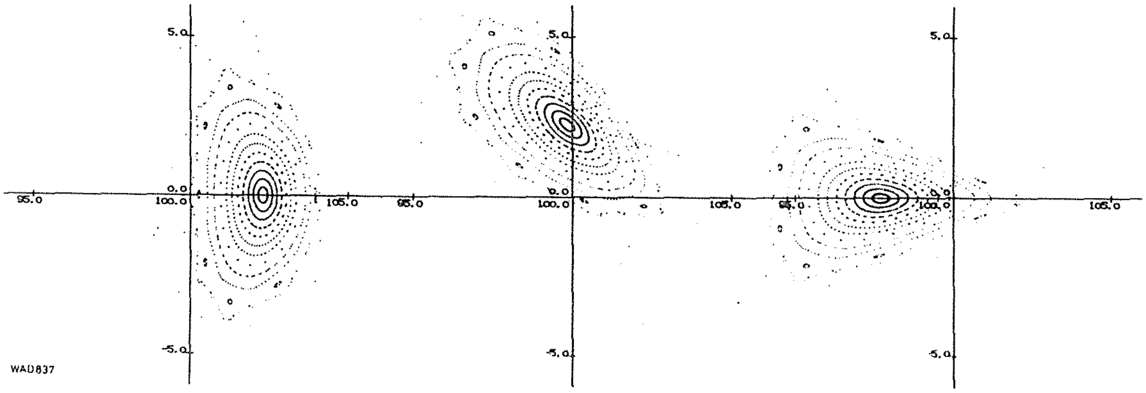
3A7

MHD Optimal Stellarator Field

W. Dommaschk, J. Nührenberg, A. Schlüter
Max-Planck-Institut für Plasmaphysik
EURATOM-Association
D-8046 Garching, Fed.Rep. of Germany

A prerequisite for the study of three-dimensional finite β stellarator equilibria and their stability by 3D numerical codes is the realization of vacuum field configurations which have promising properties with respect to the equilibirium β which can be achieved and the MHD stability of such finite β equilibria. A set of analytical vacuum fields [1] has been used to find configurations in which $\int d\ell/B$ (evaluated along a field line over one period) does not vary on magnetic surfaces (which increases the achievable equilibrium-β value, see, e.g. [2]) and in which a magnetic well fosters stability. Using a combination of numerical optimization routines and of solving boundary value problems geometrically close to those boundaries predicted by analytical theory [3] we have found field configurations which simultaneously satisfy both of the above conditions. An example with 10 periods (obtained by a combination of 17 analytical fields representing $\ell = 0, 1, 2, 3$ fields), total rotational transform of about 1.2, and toroidal aspect ratio of about 40 is shown in the figure. Obtaining lower aspect ratio appears to be difficult because of separatrix formation due to the $\ell = 3$ fields necessary for stability and of field line ergodization at the boundary of the confinement region.



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3B1

Enhanced Fusion Product Heating via Compressional Alfvén Instability*

William R. Sutton and George H. Miley
Fusion Studies Laboratory
Nuclear Engineering Program
University of Illinois
Urbana, Illinois 61801

An analytical estimate of the potential enhancement of fusion product heating is presented. Results are applicable to both D-T and advance fuel plasmas in an infinite, homogeneous, Maxwellian medium with an applied $\vec{B}$-field and an isotropic source. A positive slope in the fusion product distribution function is attained only for a sufficiently fast transient source. Once the fusion-product driven instability is initiated no external temperature ramp is required since the instability itself acts as a strong, fast-ramp negative source. In steady state the (partial) ion heating rate due only to the quasi-linear relaxation is given by

$$\dot{T}_{iI} \simeq \frac{1}{10} n_o f_R E_o \left[1 - \frac{4\eta_T}{n_o<\sigma v>\tau_s}\right] \left[<\sigma v> + \frac{2\eta_T \dot{T}_i}{n_o<\sigma v>} \frac{\partial<\sigma v>}{\partial T_i}\right] ,$$

where f_R = fraction of resonant fusion particles, n_o = background number density, η_T = threshold, τ_s = slowing down time, $\dot{T}_i$ = steady state heating rate to ions, E_o = fusion product birth energy. For the compressional Alfvén mode in a D-T plasma, collisional ion damping is shown to be the dominant damping mechanism. The external temperature ramp rate required to initiate the instability is determined. In a D-T plasma the alpha particle heating of background ions may be enhanced by 30-60%.

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*Work supported by the Department of Energy.

FRM and ION RING EQUILIBRIA for the RINGHYBRID CODE*

Alex Friedman
Electronics Research Laboratory
University of California
Berkeley, CA 94720

We have developed a new method of generating axisymmetric field reversed equilibria for the RINGHYBRID code, a linearized 3d hybrid code used for studies of the low-frequency stability of such configurations[1,2]. Equilibria of known functional form are calculated numerically, and appropriate particle initial condition and magnetic field data are used to initialize the hybrid code.

Exponential rigid rotor Vlasov equilibria, with distribution functions of the form $f \propto \exp[-(H-\Omega P_\theta)/T]$, are computed on an r-z grid using an iteration scheme similar to that of Sparks and Finn[3]. In these equilibria the current is carried entirely by hot ions with gyroradii which may range from infinitesimal (as in the Hill vortex equilibria) to the order of the system size (as in ion ring equilibria). A representation of the distribution function is obtained by assigning locations and velocities to particles in a manner which yields the correct density and mean azimuthal velocity in each grid cell, within small errors associated with finite particle size and the limited number of particles employed (several thousand). RINGHYBRID advances these particles along their equilibrium orbits in the time-independent, self-consistent zero order field. (For stability studies the code simultaneously advances linearized displacements from these orbits, as well as linearized quasineutral fluid equations for cold ion and electron components, and self-consistent first order E and B fields, which are fully 3d.)

A variety of field reversed mirror and ion ring equilibria have been obtained; when the equilibrium field and particle initial condition data are used in RINGHYBRID, particle moments remain nearly constant in time. Orbits are, in general, quite complicated, and preliminary indications are that many are truly stochastic[2]. The complexity of moderate-gyroradius FRM orbits arises from the fact that particles moving along closed field lines may or may not reflect in the high field regions, and furthermore may pass near the field null during their gyratory excursions. Also, the rate of a particle's azimuthal drifting motion depends strongly upon where it lies on its orbit in the r-z plane.

Previously, equilibria were generated by injecting bursts of particles into an external magnetic field and solving Ampere's law (with a resistive source term $-\sigma_o \partial A_\theta / \partial t$ included to damp collective oscillations) repeatedly until A_θ became nearly stationary. While this produced equilibria which were useful for ion ring stability studies[2], the new method affords greater control over the resulting equilibria, and so parameters may more readily be varied.

The package which computes equilibrium fields and particle initial conditions is called RIGIDROTOR, and is available for general use through LIBRIS on the NMFECC CDC-7600.

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*Research supported by the U.S. Department of Energy under Contract No. DE-AS03-76SF00034, Project Agreement No. DE-AT03-76ET53064.

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POSTER SESSION PREFERRED

Simulation of Rotation in Linear Magnetic Systems*

F. L. Cochran, R. Morse, and G. Sowers
The University of Arizona
Tucson, Arizona 85721

A model for treating rotation has been implemented in the 1-½ D lagrangian code PINECONE. This code uses a full dimension along the magnetic field axis and a sharp boundary at the interface between the plasma and vacuum. The rotational variables are treated in a thin shell approximation at the interface.

Rotation has been observed in theta pinch plasmas for several years and is known to be a source of instability.[1] The mechanism for rotation has been explained as end shorting of the radial electric field. In the case of complete end shorting, the ions rotate with an angular velocity equal to the diamagnetic drift velocity. In the early phase after the initial shorting, the rotation propagates up the plasma column at the Alfvén speed. We are presently studying this mechanism for Los Alamos type theta pinch parameters.

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*Research supported by USDOE

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3B4

Force-Free Magnetic Fields in Non-Circular Cylinders*

Cheng Chu and Ming-sheng Chu

General Atomic Company
San Diego, California 92138

ABSTRACT

The structure of force-free magnetic fields $\nabla \times \vec{B} = \mu\vec{B}$ (with μ a constant in space) surrounded by various non-circular conducting walls has been studied. The boundary cross-sectional shape and size are assumed constant along the axial direction z. It is shown that fixed boundary solutions for arbitrary μ can be constructed from the eigenfunctions $\{\psi_\nu\}$ of the Helmholtz equation $(\nabla^2 + \lambda^2)\psi = 0$ with $\psi = 0$ on the conducting walls. Taylor's profile was recovered by this approach in the limit of a circular cross-section. Force-free structures of arbitrary cross-section are stable to the axial-symmetric mode if $\mu < \lambda_s$, where λ_s is the lowest eigenvalue λ_ν associated with the eigenfunction satisfying $\int\psi_\nu dA = 0$ over the cross-section area. The differences between circular and non-circular cases will be discussed.

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*Work supported by General Atomic Company.

POSTER SESSION

CALCULATIONS OF NEUTRAL BEAM POWER DEPOSITION FOR DOUBLET III

R. W. Harvey, D. K. Bhadra, and S. C. Chiu

General Atomic Company
San Diego, California 92138

ABSTRACT

A new Monte Carlo guiding-center orbit code, MCGO, gives the spatial profiles of energy deposition on electrons and ions and power to the wall/limiter, resulting from neutral injected hot ions. The guiding-center orbit calculation is based on the ORNL code, FLOC,[1] valid for arbitrary cross-section plasmas. The Monte Carlo technique is applied to Coulomb pitch angle scattering, and to charge exchange with a background neutral distribution. We also estimate effects of microturbulence on the orbit, using Monte Carlo simulation of a quasilinear diffusion operator. Initial conditions for the hot ions are determined by the hot ion birth rate profile, calculated with NFREYA.[2] Application is made to doublet- and dee-shaped plasmas in Doublet III.

Work supported by Department of Energy, Contract DE-AT03-76ET51011, GA Project No. 3235.

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Similarity Solutions for Decay and Rotation Generation in a Reversed Field Theta Pinch

John M. Finn
Science Applications Inc., McLean, Va.

Wallace Manheimer
Naval Research Laboratory, Washington, D.C.

In order to elucidate the problem of transport and rotation generation in a compact torus, we show that similarity solutions exist to the transport equations. An examination of the data from FRX-B (particularly a comparison of the decay rates of particles and energy) indicates the presence of an anomalous resistivity which appears to dominate any possible anomalous thermal conduction. Therefore the simplest relevant model equations which can describe the system are

$$\frac{\partial A}{\partial t} + V \frac{\partial A}{\partial X} = \frac{\eta}{4\pi} \frac{\partial^2 A}{\partial X^2} \qquad (1)$$

$$\frac{1}{8\pi}\left(\frac{\partial A}{\partial X}\right)^2 + nT = n_o T \qquad (2)$$

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial X} nV = 0 \qquad (3)$$

where A is the vector potential (flux function), T is assumed constant and n_o is the density at X = 0. The problem is formulated in slab geometry with the field null $\partial A/\partial X = 0$ at X = 0 and the separatrix A = 0 at $X = X_o$. This formulation can easily be generalized to cylindrical geometry, T ≠ constant, etc.

We consider a similarity solution $A(X,t) = A(X)e^{-\gamma t}$, $n(X,t) = n(X)e^{-2\gamma t}$ and $V(X,t) = V(X)$. This requires the separatrix to be fixed in time as observed in the experiments. Equations (1)-(3) can be solved by a simple iteration scheme. First assume an eigenvalue γ and n(X) and solve Eq. (3) for V(X). Then solve Eq. (1) for A and γ as an eigenvalue equation, solve Eq. (2) for n(X) and iterate until the process converges. In practice this iteration scheme converges quickly, and it gives very reasonable profiles. It turns out that the decay time, γ^{-1}, is about twice as long as for resistive flux diffusion alone, uncoupled to plasma flow. The reason is that the plasma flow is outward while the resistive diffusion is inward.

Since the resistance is anomalous, it most likely arises from a plasma instability. From the properties of the micro-instability, one can determine the anomalous torque on the plasma as well as the anomalous resistivity. We examine the question of rotation generation by the lower hybrid drift instability and compare the results with FRX-B.

3B7

ZT-40 Startup Models

R. N. Byrne and C. K. Chu*
Science Applications, Inc.**
Laboratory for Applied Plasma Studies
La Jolla, CA 92037

We have tried to simulate the assembly phase of the Los Alamos RFP experiment, ZT-40, for the (slow) case, in which the risetimes are in the order of a hundred microseconds, using the G2M transport code run in 1D mode. We have investigated the ability of various arbitrary enhancements to classical transport to reproduce the observed behavior for forced-reversal cases. The enhancements used were:

1) Braginskii transport times a large constant.
2) 1/n and $\sqrt{T_e}/n$ electron heat flow and particle flow.
3) Chodura electrical resistivity.
4) The above plus 1/n heat and particle flow.

In all the runs the plasma buildup resulted in initially hollow density profiles, which tended to fill in at various rates, and hollow temperature profiles, which did not. The toroidal current tended to peak off-axis, but could be flattened if the resistivity were sufficiently large.

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*Permanent address: Columbia University, New York, New York.

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KINETIC MODELING OF HOT ELECTRON RINGS

D. C. Baxter
Science Applications, Inc., La Jolla, California

The implications of an electron distribution function are considered for EBT and tandem mirror barriers. The distribution function is consistent with quasi-linear diffusion caused by electron cyclotron resonant heating in an inhomogeneous magnetic field. A critical parameter is the energy above which the quasi-linear effects of the $n = 2$ harmonic resonance will dominate collisions. The consequent longitudinal dependence of density and parallel and perpendicular pressure are calculated.

Interchange Mode Growth Rates Around the Magnetic Axis*

J.J. Ramos and T.M. Antonsen

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Growth rates for unstable, ideal MHD modes in the vicinity of the magnetic axis of an axisymmetric plasma are obtained from a perturbative solution of the dispersion equation for high toroidal number incompressible displacements. This method[1,2] requires a two scale analysis in the poloidal variable.

The original formulations[1,2] were restricted to consideration of configurations which were marginally stable on axis ($q_o = 1 +$ ellipticity corrections[3]). We have developed two methods by which this constraint can be relaxed.

First, for cases which are near marginal stability, we obtain a distilled dispersion equation of the same form as obtained in Refs. 1 and 2 but which contains the interaction of the localized interchange and ballooning mode.

Second, for cases which are far from marginal stability, we obtain the following expression of the squared growth rate:

$$-\omega^2 = \frac{8 v_{Ao}^2 \psi \beta_p (q_o^{-2} - 1)}{R_o^4 B_o q_o} \left[1 + \sum_{n=1}^{\infty} c_n \left(\frac{\psi q_o}{R_o^2 B_o \beta_p (q_o^{-2} - 1)} \right)^{\frac{n}{2}} \right] ,$$

and compute explicitly the first three terms of this series. This growth rate is essentially that of the localized interchange modes but with corrections due to slight ballooning of the displacement.

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

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POSTER PRESENTATION

3B10

Effects of $q(\psi)$ on the Ballooning Mode Second Stability Region*

L. Sugiyama and J. W-K. Mark[+]

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

A numerical investigation of a series of tokamak equilibria derived from flux conserving sequences shows that the second stability region for ideal MHD ballooning modes with large toroidal mode number is very sensitive to the $q(\psi)$ profile. For equilibrium sequences with the same flux surface geometries but scaled $q(\psi)$ it is seen that as $q(\psi)$ increases stability improves near the magnetic axis, leaving a stable region at small shear and also that the high β second stability region, absent at low $q_o \lesssim 1$, appears and increases in size so that the unstable region narrows considerably (measured in terms of β at constant shear $\hat{s} = d\ell nq/d\ell nr$). A smaller aspect ratio is found to make the plasma even more sensitive to this stabilization.

It is also shown that the "disconnected mode" approximation (1) where the eigenfunction is assumed to vanish at the inside edge of the torus gives a good qualitative estimate of the second stability boundary even for the relatively small aspect ratio $R_o/a = 2.5$. The "disconnected" results and results obtained from a solution in the infinite domain via the ballooning transformation and differ considerably at low β and near the magnetic axis where the mode is less strongly ballooning.

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(1) B. Coppi, Phy. Rev. Lett. 39, 939 (1977).

*Research sponsored by the U.S. Department of Energy.

[+] Lawrence Livermore Laboratories, Livermore, CA 94550

Please post adjacent to "MHD Stable Confinement Configurations in High-β Regimes" by A. Ferreira, B. Coppi and J.J. Ramos.

MHD Stable Confinement Configurations in High-β Regimes*

A. Ferreira, B. Coppi, J.J. Ramos
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

At finite values of β, axisymmetric magnetic confinement configurations tend to acquire characteristics that hinder the onset of MHD instabilities driven by the combined effects of magnetic curvature and plasma pressure gradient. The most noticeable consequence is the existence of a second regime of stable configurations at high β.[1] A simple dispersion relation describing these effects has been derived analytically in the vicinity of the magnetic axis.[2]

Values of the inverse rotational transform above the threshold for localized interchange instability further reduce the size of the unstable region and make the two stable domains connected in parameter space. Thus it is possible to attain high β regimes through a thoroughly stable sequence of flux conserving equilibria. To show this we have used an analytical moderate-β model with shifted near circular magnetic surfaces; the limit of validity for this model, at peak β of the order of 10% and poloidal β about half the aspect ratio, can be reached without exciting any ballooning instability. Higher β limits are therefore expected from detailed numerical analysis with optimal shaping of the flux surfaces and the equilibrium profiles.

Solutions of the time dependent linearized MHD equations are presented in order to show the evolution of shear-Alfvén waves in stable configurations. In addition to a transient growth, a pulse is distorted in shape and, if the equilibrium configuration is close to the threshold for ballooning instability we observe the formation of modes localized on the outside of the torus.

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

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Please post adjacent to "Effects of $q(\psi)$ on the Ballooning Mode Second Stability Region".

STABILIZATION OF THE M=2 TEARING MODE BY THE ELECTRON TEMPERATURE GRADIENT

N. T. Gladd, J. F. Drake, Y. C. Lee, and C. S. Liu
Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20742

The electron temperature gradient T_e' has been shown to strongly influence the stability of microtearing (high m modes with $\Delta'<0$) modes.[1] Modes with $\omega_* \sim \nu_{ei}$ are strongly destabilized by T_e' while modes with $\omega_* \gtrless \nu_{ei}$ are strongly stabilized. The electron temperature gradient is similarly found to dominate the stability properties of the magnetically-driven global tearing modes (m=2,3 with $\Delta'>0$). The stability properties of this mode are important because of their role in major disruptions in tokamaks.[2]

In preliminary calculations, we have imposed $\Delta'>0$ boundary conditions on the asymtotic behavior of the flux perturbation $\tilde{A}_{\parallel}$ in slab geometry. For values of $\eta_e = d\,\ell n\,T_e/d\ell n\,n$ and Δ' appropriate to the m=2 mode in present tokamak discharges, the temperature gradient can either stabilize or enhance the growth rate of the tearing mode, depending on the collisionality ω_*/ν_{ei}. The stabilizing influence of T_e' arises from large parallel currents which flow as the magnetic field is tipped along ∇T_e. These results are presently being extended to cylindrical geometry by retaining the parallel current and matching the kinetic solutions to the cylindrical MHD solutions[3] outside the rational surface. Initial emphasis will be placed on understanding the effect of cylindrical geometry on collisionless tearing modes.

*Supported by U.S. Department of Energy.

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3B13

The Case for the Electron Energy Loss in Tokamaks Being Mainly an Energy Transfer to the Ions

A.A. Ware

Fusion Research Center
The University of Texas at Austin
Austin, Texas 78712

Abstract

There is growing experimental evidence for substantial anomalous energy transfer from electrons to ions[1,2]: (a) in the outer regions where $T_i > T_e$ more energy is given back to the electrons by collisions than the ions receive by collisions in the central region; (b) the transient decay of T_i after neutral beam turn off gives τ_{iE} from 2 to 5 times smaller than obtained from $W_i/(P_{ei}+P_{beam})$. There are, in fact, several neoclassical mechanisms which produce such energy transfer, namely, (1) direct ohmic heating of the ions caused by the ion bootstrap current J_{iz} driven by the ion heat conduction ($P_{i\Omega} \hat{=} J_{iz} E_\varphi$); (2) if the neoclassical component of the diffusion is inwards, the poloidal phase of the electron pressure tensor is such as to cause "magnetic pumping cooling" of the electrons driving magnetic pumping heating of the ions; and (3) the poloidal rotation instability which accurately predicts the onset of the sawtooth disruptions causes periodically much more rapid energy transfer from the electrons to the ions by process (2). In addition, many instabilities (resistive modes, driftwaves) will cause some viscous heating of the ions. Lastly, if it is assumed that most of the ohmic heat is conducted out by the ions, i.e., $q_i \simeq E_\varphi B_\theta / 4\pi$, using the plateau ion heat conductivity and the limiting condition on T_{eo} caused by the poloidal rotation instability, (for ohmically heated discharges $(T_{eo}/T_{io})^{\frac{1}{2}} \sigma_{\parallel} E_\varphi = 0.47 (m_i/m_e)^{\frac{1}{2}} n_{io} e v_{Tz}$) the scaling for T_{eo} is $T_{eo} = e^{-13.4} a^{-5/4} RIZ_{eff}^{\frac{1}{2}} (n^o B^o A_i^o)$. All eight exponents agree with the empirical scaling of Pfeiffer and Waltz, except for two 10% errors.

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1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

STRONG TURBULENCE, WAVES, AND THE FAILURE OF WEAK TURBULENCE THEORY*

Harvey A. Rose, CTR-Division and Donald F. Dubois, T-Division
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

The oscillating two stream instability, and the closely related modulational instability, are not well described by a weak turbulence theory when fluctuation-fluctuation interactions dominate the fluctuation-mean field interactions.

In the context of a three mode model of coupled Langmuir and ion sound waves, we compare Monte Carlo simulation with the direct interaction approximation and find satisfactory agreement for growth rate, steady state spectrum, and steady state phase correlation data.

*This work performed under the auspices of the U.S. Department of Energy.

EQUILIBRIUM AND ADIABATIC COMPRESSION OF A FREE BOUNDARY DOUBLET*

Shih-liang Wen
Mathematics Department, Ohio University, Athens, Ohio 45701

Harold Grad
Courant Institute of Mathematical Sciences, New York University
New York, New York 10012

The equilibrium shape and location of a plasma doublet is studied by neglecting the toroidal curvature effects. In contrast to previous investigations which assume the free boundary profile be convex, inflection points are included on the sharp plasma boundary supported in equilibrium by a vacuum magnetic field. Using conformal mapping, a one-parameter family of explicit solutions are obtained. The plasma shape is unquely determined by initial thermodynamic parameters and outer wall current. Numerical computations show that there are limitations on the adiabatic compression ratio. Under high compression ratios the column cross-section becomes convex. In a limiting case our solution becomes the solution of a free boundary problem with infinite extent (an idealized problem).

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3B16

Effects of the Fast Wave on the Drift-Cyclotron Loss-Cone Mode*

Ker-Chung Shaing
Nuclear Engineering Department
University of Wisconsin-Madison
Madison, WI 53706

Particle orbits in the presence of the fast wave fields, such as those used in ICRF heating, are calculated. We find that the resonant interaction of ions with the wave can be neglected at $\omega_o = 2\omega_{ci}$ provided that the wave electric field strength is less than a critical value E_c. The dominant effect on the dispersion relation for the drift-cyclotron loss-cone mode is thus found to be due to the non-resonant effects of the wave on electrons and ions. We find that a fast wave with $\omega_o = 2\omega_{ci}$ destabilizes the mode. For $\omega_o < 2\omega_{ci}$, fast waves can stabilize the mode for certain values of plasma β: e.g., $\beta \sim 1$. The wave electric field strength required for a significant stabilization effect on the mode is about 100 V/cm $(k^2V_E^2/\omega_o^2 \sim 0.1)$ for the Phaedrus experiment and may be achieveable experimentally.

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3B17

Ballooning Formalism Calculation of Electromagnetic Trapped-Particle Modes*

G. Rewoldt, W.M. Tang, and E.A. Frieman
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

Our previous calculation[1] of the electrostatic trapped-electron mode, employing the ballooning formalism, has now been generalized in several ways. A more general integral form of the ion response, valid for an arbitrary ratio of the mode frequency to the ion transit frequency and for arbitrary $k_\perp\rho_i$ and $k_\perp\rho_{bi}$ (ρ_i = ion gyroradius, ρ_{bi} = ion banana width), is employed. This allows the trapped-ion mode,[2] as well as the trapped-electron mode,[3] to be obtained from a single code. The calculation includes multiple ion species[4] such as impurities. The code has recently been extended to solve the parallel and perpendicular components of Ampere's law, as well as the quasi-neutrality condition, for the parallel and perpendicular components of the perturbed vector potential, along with the perturbed electrostatic potential. Thus the calculation can recover the shear-Alfvén branch as well as the drift branch, in both the trapped-electron mode and trapped-ion mode frequency ranges. The code will be employed to study kinetic effects on ideal and resistive high-n MHD ballooning modes. Illustrative results will be presented.

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

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-. 3B18

Scattering of Lower-Hybrid Waves by Density Fluctuations*

P.L. Andrews and F.W. Perkins
Plasma Physics Laboratory, Princeton University
Princton, NJ 08544

A simplified slab geometry is used to simulate the scattering of wave-guide injected lower-hybrid waves in a tokamak by a turbulent outer layer. The density fluctuations are considered to be time independent and to have ($\delta n/n$) in the range 0.01 - 1. In this regime, the full linearized wave equation is solved numerically and the results averaged over many realizations of the scattering layer and displayed as functions of magnetic field strength, wavelength, etc. Preliminary results for Alcator-type parameters show heavy scattering with a resultant almost isotropic flux spectrum. This is important not only because of power lost to back-scattering but also due to the effects of magnetic shear which lead to rapid absorption of the scattered waves.

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3B19

RESONANT ABSORPTION OF ALFVÉN WAVES*

P. L. Pritchett and E. Canobbio⁺
Center for Plasma Physics and Fusion Engineering
University of California, Los Angeles, California 90024

The resonant absorption of Alfvén waves is investigated numerically using a finite-resistivity MHD code. In particular, the response of a plasma slab to an oscillating field on the boundary is studied. Solutions in the resistive layer are found to reach a steady state after an initial growing period, as has been predicted theoretically[1]. Results with the linear code indicate that the Ohmic heating is small for ka << 1 but can be appreciable for ka = O(1). Here k is the pump wavenumber and 2a is the separation between resonant surfaces. The implications of this result for heating in tokamaks will be discussed. Nonlinear modifications of these results are currently being investigated.

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[*] Work supported by USDOE and NSF.

[+] Permanent address: Association EURATOM-CEA, Centre d'Etudes Nucleaires, 38041 Grenoble, France

[1] J. M. Kappraff and J. A. Tataronis, J. Plasma Physics, 18, 209 (1977).

POSTER SESSION PREFERRED.

1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

THE DISPERSION FUNCTIONAL FOR A TWO-COMPONENT VLASOV PLASMA AND FOR THE VLASOV-FLUID MODEL*

Keith R. Symon
University of Wisconsin
Madison, Wisconsin 53706
and
C. E. Seyler and H. Ralph Lewis
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

The dispersion functional introduced by Symon, Seyler, and Lewis[1] for linear stability studies of Vlasov equilibria is applied to a two-component Vlasov plasma and to the Vlasov-fluid model. The application to the Vlasov-fluid model involves an extension of the earlier work. The dispersion functional is presented in detail for the two-component Vlasov plasma in cartesian coordinates and for the Vlasov-fluid model in cylindrical coordinates. Stability theorems that can be derived from the dispersion functional are discussed.

*This work performed under the auspices of the U.S. Department of Energy.

1. K. R. Symon, C. E. Seyler, and H. R. Lewis, submitted to J. of Plasma Phys. for publication.

3B21

Finite Larmor Radius Stabilization of Ballooning Modes*

K. T. Tsang and J. Whitson

We present here a new derivation of the ideal MHD ballooning eigenmode equation from the gyro-averaged Vlasov equation. This derivation goes beyond previous work[1,2] in literature and takes into account finite Larmor radius (FLR) and kinetic effects easily. In the fluid ion and electron limit and circular magnetic flux surface equilibrium, the following eigenmode equation is obtained

$$\frac{\partial}{\partial k_x}(k_x{}^2 + b_y{}^2)\frac{\partial}{\partial k_x}[1-\tau(\Gamma_o-1)\frac{\omega-\omega_{*i}}{\omega-\omega_{*e}}]\hat{\phi}$$

$$= \Big\{\beta(R/L_n)(q/\hat{s})^2(\cos k_x\Delta + (k_x/k_y)\sin k_x\Delta)[1 + (1-\omega/\omega_{*i})(\Gamma_o-1-b(\Gamma_o-\Gamma_1)/2)/(1+\tau)]$$

$$+ \omega(\omega-\omega_{*i})(\Gamma_o-1)\Omega_o{}^2\Big\}\hat{\phi} \qquad (1)$$

where k_x and $k_y = m/r$ are the radial and poloidal wave numbers, m and ℓ are the poloidal and toroidal mode numbers respectively, $\Gamma_o = I_o(b)\exp(-b)$, $b = (k_x{}^2 + k_y{}^2)\rho_i{}^2$, $\hat{s} = rq'/q$, $\Delta = 1/\ell q'$, $\tau = T_e/T_i$, $L_n^{-1} = \partial\ell nN/\partial r$, $\Omega_o = k_y\lambda_{Di}cs/Rq$ and the rest of the notation is standard. The FLR modification to the field line bending term is due to the quasi-neutrality condition, while the modification to the driving term and the inertia term is due to Ampere's Law. The inertia term in Eq. (1) agrees with that of Chu et al[1] and Lee and Van Dam[2] in the small FLR limit. The FLR correction is important because near critical β the eigenfunctions extend to large $k_x\rho_i$.

Numerical solutions for Eq. (1) have been pursued. Preliminary results indicate that FLR effects are stabilizing and critical β can be increased.

The extension of Eq. (1) to more realistic geometry and electron dynamics will be discussed.

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

[1] M. S. Chu, C. Chu, G. Guest, J. Hsu and T. Ohkawa Phys. Rev. Lett. 41 247 (1978)

[2] Y. C. Lee and J. W. Van Dam, Proceedings of the Finite Beta Theory Workshop, Sept. 1977, Varenna, Italy

3B22

Third Order Reduced Equations for Tokamaks

H. Strauss

Courant Institute of Mathematical Sciences

New York University

Abstract

Finite beta reduced equations[1] have been derived by expanding the MHD equations in $\varepsilon = a/R$, the inverse aspect ratio, assuming $\beta \sim \varepsilon$, $q \lesssim 1$. Now the equations have been expanded to the next higher order, ε^3 , so that poloidal curvature and other toroidal corrections are included. The extra terms are needed to obtain a more accurate average curvature term at low beta, and to obtain equilibria satisfying a more accurate version of the Grad-Shafranov equation. The equations should be useful for calculating ballooning and interchange effects on tearing modes. Another application is the study of the high beta stabilization of ballooning modes[2]. It has been found that poloidal curvature has a destabilizing effect, requiring a threshold alue of ε/q^2 for stability.

1. H.R. Strauss, Phys. Fluids, 20, 1354 (1977)
2. H.R. Strauss, W. Park, D.A. Monitcello, R.B. White, S.C. Jardin, M.S. Chance, A.M.M. Todd, and A.H. Glasser, PPPL - 1535, (1979)

R.E. Potok, P.A. Politzer and L.M. Lidsky
Plasma Fusion Center
and
Department of Nuclear Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

ABSTRACT

ENERGY CONFINEMENT AND TRANSPORT IN TORSATRONS. Energy and particle confinement properties of a torsatron were investigated with the aid of a computer code utilizing guiding-center equations accurate to second order in μ. Multi-dimensional cubic-spline interpolation was used to calculate B, ∇B, and E in a highly efficient manner. Background plasma profiles of voltage, electron temperature, and density were mapped onto the flux profile, and these plasma properties were used to calculate drag and velocity diffusion forces on the test particle. Many orbit tracks were combined to yield an α-particle distribution function and fractional energy confinement. Results show an overall α-particle percentage power confinement in torsatrons of 99% for $R_o/a = 12$, 90% for $R_o/a = 6$, and 65% for $R_o/a = 3$. Loss regions in phase space for the thermal plasma ions were also mapped. These data were used to calculate an energy containment time necessary for ignition.

The ion thermal conductivity (χ_i) in torsatron configurations was measured by analyzing the interaction of a test particle distribution with a background plasma. For each measurement, 360 test ions were launched on a given flux surface. These test ions had a pitch angle and energy distribution appropriate to an isotropic Maxwellian with temperature equal to that of the background ions, and were uniformly spaced poloidally. The kinetic energy distribution function $U_i(x,t) = \int d^3v f_i(x,v,t) \frac{1}{2} m_i v^2$ was created, and χ_i was determined by

$$\chi_i = \frac{\frac{1}{t}\int dx \, \frac{1}{2} \, (x-x_o)^2 \, U_i(x,t)}{\int dx \, U_i(x,t)}$$

Numerical calculations of χ_i showed the presence of a plateau regime extending over two orders of magnitude in collision frequency. The value of the ion thermal conductivity was approximately equal to the neoclassical plateau value for an equivalent torus without helical modulation. The predicted adverse 1/v behavior due to ripple trapping was not seen.

Results indicate that a moderate aspect ratio torsatron ($R_o/a \cong 10$) can be ignited with T_i = 10-20 keV. This work supported by the Department of Energy.

3B24

Abstract Submitted
for the Sherwood Theory Meeting
April, 1980

Electron Cyclotron Radiation Emission from a Mirror Plasma.* C.M. CELATA, Dartmouth College.--Electron cyclotron emission and absorption from a mirror plasma occur predominantly in the "extraordinary mode" - i.e., the mode which is the extraordinary mode for propagation perpendicular to the magnetic field. The "extraordinary mode" emission spectrum is calculated for both the fundamental and second harmonic, assuming TMX end cell parameters. A slab model is used for the plasma, and observation is assumed to be such that $k_{11} >> \omega/c\sqrt{kT_e/m_e c^2}$ (Doppler regime). The electrons are assumed to have a Maxwellian distribution function, with spatially uniform temperature. Electron cyclotron radiation absorption is examined by calculating optical depth vs frequency for various observation lines through the plasma and plasma densities. Effects of the cutoffs and upper hybrid resonance layer in the cold plasma approximation are demonstrated.

*Work supported in part by the National Science Foundation.

Christine M Celata

Christine M. Celata

3B25

Coherent Wave-Particle Effects in EBT Annulus Formation*

D. B. Batchelor and R. C. Goldfinger
Oak Ridge National Laboratory, Oak Ridge, Tennessee

The annulus in EBT is observed to form at the location of the second harmonic cyclotron resonance. However, for a low temperature plasma such as in the surface region of EBT-I the linear second-harmonic resonance interaction is quite weak being reduced by a factor $k_\perp^2 \rho_e^2 \sim 10^{-4}$ from that of the fundamental. Single particle orbit calculations are presented which suggest that coherent, wave-particle interactions may be important in producing the annulus from a population of particles having small initial perpendicular energies. It is shown that the heating is highly pitch-angle dependent and that the motion of particles with large initial pitch angle is superadiabatic rather than stochastic as is assumed by quasilinear models. Relativistic effects are found to be quite important even at moderate energies. The adiabatic sloshing energy ($\Delta E > 500$ ev for parameters appropriate for EBT-I) is much larger than the quasilinear energy step size. Randomizing effects of multiple waves, ∇B drifts and collisions will also be discussed.

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3B26

Drift Waves in Cylindrically Symmetric Systems with Strong Magnetic Shear*

Ralph Linsker
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544

An integral-equation formalism has been developed to treat electromagnetic drift waves in cylindrically symmetric geometry, incorporating effects due to magnetic shear, density gradients, ion magnetic drifts, and electron current. A term of leading order in the expansion parameter ε (= ion gyroradius/system size) is identified; this term persists in the electrostatic slab-model limit but has not been taken into account in several drift-wave stability proofs using that model. This term (in the denominator of the perturbed-ion-density part of the dispersion relation) is found to affect the eigenmode structure for the case of strong shear ($L_s \sim L_n$), though it alters the mode frequency only slightly. For the case of the (electrostatic) electron diamagnetic drift branch, the mode damping rate is found to be extremely insensitive to ion temperature gradient, electron current, and ion magnetic drifts, in the strong-shear regime. An electron stream velocity that is a substantial fraction of the electron thermal speed is required to destabilize the drift mode for a typical strongly-sheared case ($L_s/L_n = 6$). This indicates that, within the limitations of the model employed here, a cylindrical reversed-field Z-pinch is expected to be unstable to the electron diamagnetic drift branch (in the collisionless electrostatic limit) only at such low densities that $\beta \lesssim$ several times the electron Larmor radius/system size. Conclusions drawn from these numerical stability studies are expected to be modified by electromagnetic effects. Some aspects of these modifications will be discussed.

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POSTER SESSION

Model for Particle Transport in Tokamaks*

N. Sharky and B. Coppi

Massachusetts Institute of Technology
Cambridge, MA 02139

Steady state particle balance is analyzed in a variety of discharges where the neutral mean free path is much smaller than the plasma radius ($\lambda_{mfp} << a$), and $Z_{eff} \simeq 1$. The collisional particle flux Γ^{coll} and the particle source term, in the continuity equation, are evaluated using measured data and the results of a Monte Carlo code. An empirical expression is sought for the anomalous particle flux Γ^{an}, which would enable us to reproduce the measured density profiles in these discharges.

First the possibility that $\Gamma^{an} = -D_p \partial n_e / \partial r$ is investigated, and various empirical expressions for the diffusion coefficient D_p, proposed recently by other authors, are considered. Solving the continuity equation for n_e, it is found[1] (for the class of experiments described above) that this expression for Γ^{an} yields flat density profiles, in the main inner region of the plasma, which are not consistent with the measurements.

Then the anomalous particle flux is written[2,3] as $\Gamma^{an} = -D_p \partial n_e / \partial r - 2\alpha_p D_p n_e r / a^2$, with $D_p \simeq D^e_{th}$. The form of the electron thermal diffusion coefficient D^e_{th}, which is obtained from the steady state electron energy balance equation[2], was found earlier to be consistent with various experiments. Simulation of the density profiles in a variety of discharges[1] (Alcator, FT, PLT, and T-10) provides us with a considerable amount of information on the coefficient α_p, which determines the magnitude and features of the anomalous inward flux. A general expression for α_p, showing its radial variation and its dependence on physical parameters, will be given.

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

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POSTER PRESENTATION

The Resonance Absorption of Axially Asymmetric Alternating Fields in a Inhomogeneous Plasma.

V. I. Laphsin*, J. L. Shohet, The University of Wisconsin, Madison,
K. N. Stepanov, A. M. Gorkii Kharkov State University, Kharkov, USSR.

We have studied the absorption by an inhomogeneous plasma cylinder of electromagnetic perturbations produced by axially asymmetric alternating electric currents with a frequency ω much smaller than the ion cyclotron frequency. Currents flow outside the plasma. We assume that the weakly inhomogeneous DC magnetic field $\vec{B}_o$ has both longitudinal and azimuthal components but $B_{o\phi} << B_{oz}$, We consider the acoustic resonance case when the phase velocity ω/K_{11} of the pump wave is approximately equal to the acoustic velocity ($T_e >> T_i$, K_{11} is axial wavenumber). At resonance in a narrow layer or throughout the volume, the energy absorption rate is larger than in the nonresonant case by a factor of $(T_e/T_i)^{3/2}$ and $(T_e/T_i)^{3/2}$ $(M_i/M_e)^{1/2}$ respectively. We also show that when in the resonant layer, the pump frequency is approximately equal to the drift-wave freqeuncy $[\omega \approx \omega^* \ (T_e/T_i)$, $\omega^* = (mv^2_{T_i}/r\omega_{B_i})\ (\partial \ln n_o/\partial r)$, $Z_i = (\omega/\sqrt{2}\ K_{11}\ v_{T_i}) >> 1$, $Z_e << 1$, $T_e >> T_i$, n_o is the plasma density, m is mode number] and instabilities can be suppressed by influence of the inhomogeneous DC magnetic field, the energy of electromagnetic perturbations can be converted into the thermal energy of the plasma. For example, when the conditions

$$\left(\frac{\partial \ln B_{oz}}{\partial r}\right)_{r=0} > 0, \quad \left(\frac{\partial \ln B_{oz}}{\partial r}\right)_{r=0} > \left| \frac{(r-r_o)}{r_o Z_e} \ \frac{T_e}{T_i} \ \Delta \right|, \quad r_o \left(\frac{\partial \ln B_{oz}}{\partial r}\right)_{r=0} > \frac{B_{o\phi}}{B_{oz}} \ \frac{1}{Z_e{}^2},$$

[$\Delta \equiv d\ (T_i/T_e + \omega^*/\omega)/dr$, $r-r_o$ is the resonant region] are satisfied the heating rate can be enhanced:

$$\frac{dT}{dt} \sim \omega \ T_i \left(\frac{\tilde{B}}{B_o}\right)^2 \left(\frac{\partial \ln B_{oz}}{\partial r}\right)_{r=0} \frac{Z_e \ r_o^2}{\Delta^2 \ (r-r_o) \ a^2} \ \frac{T_i}{T_e} \left| \ \mathrm{Im} \ (K_{11} \ r_o) \right|^2 .$$

Here $B^{\sim}$ is the peak pump field in the plasma, a is the plasma radius and Im(x) is the modified Bessel function. This heating rate is larger than in the nonresonant case and is even larger than in the case of acoustic resonance. If however $Z_i \lesssim 1$, the inhomogeneous magnetic field cannot suppress drift-wave instabilities and energy is lost to these instabilities (the energy absorption rate can actually become negative).

* Permanent address: A. M. Gorkii Kharkov State University, Kharkov, USSR.

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RESONANT ABSORPTION OF ALFVÉN WAVES*

P. L. Pritchett and E. Canobbio⁺
Center for Plasma Physics and Fusion Engineering
University of California, Los Angeles, California 90024

The resonant absorption of Alfvén waves is investigated numerically using a finite-resistivity MHD code. In particular, the response of a plasma slab to an oscillating field on the boundary is studied. Solutions in the resistive layer are found to reach a steady state after an initial growing period, as has been predicted theoretically[1]. Results with the linear code indicate that the Ohmic heating is small for $ka << 1$ but can be appreciable for $ka = O(1)$. Here k is the pump wavenumber and $2a$ is the separation between resonant surfaces. The implications of this result for heating in tokamaks will be discussed. Nonlinear modifications of these results are currently being investigated.

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[1] J. M. Kappraff and J. A. Tataronis, J. Plasma Physics, 18, 209 (1977).

POSTER SESSION PREFERRED.

BALLOONING MODES IN MULTIPLE MIRRORS

Thomas B. Kaiser
Lawrence Livermore Laboratory, University of California
Livermore, California 94550
and
Guy Vandegrift
Electronics Research Laboratory, University of California
Berkeley, California 94720

ABSTRACT

The Multiple-Mirror Experiment[1] is designed to have "minimum-average-B" and, therefore, flute-interchange stability. Consequently, the maximum β achievable in such a device is limited by ballooning modes. The computer code developed to investigate ballooning modes in tandem mirrors[2] has been modified to accommodate multiple mirror configurations and used to study their stability. The code assumes large-aspect-ratio ordering of the guiding-center energy principle, eikonal representation of the transverse (to $\underset{\sim}{B}$) variation of the perturbation, isotropic pressure, long-thin finite-β modification of mod-B and vacuum field line geometry.

The structure of the marginal stability hypersurface in the relevant parameter space is determined by solving the appropriate eigenmode equation numerically for the lowest perturbed-state in its spectrum.

Critical β values predicted by the code have been compared with analytic estimates obtained by balancing the net driving (curvature) and restoring (line-bending/stretching) forces computed using reasonable trial functions for the mode amplitude.

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

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2. T.B. Kaiser, "Numerical Investigation of the Ballooning Stability of TMX at Finite-β," Bull. of the Am. Phys. Soc. 23, 754 (1978).

1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

RESISTIVE TEARING MODES IN THE FIELD REVERSED THETA PINCH*

Thomas G. Hewitt
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

The one-dimensional linear resistive eigenvalue code of Freidberg and Hewett is used to investigate resistive modes in the Field-Reversed Theta Pinch (FRTP).

Rigid rotor equilibria, which are consistent with long but finite length theta pinch configurations are investigated. Finite length effects upon the eigenfunctions/eigenvalues are ignored, however. Both n = 0 and n = 1 (where n is the toroidal mode number) are found to be unstable for these profiles. No unstable modes are found for n = 2 or greater. The growth rate of the n = 1 mode is greater than that of the n = 0 mode in all cases seen so far. These growth rates increase strongly with increasing resistivity, and seem to vanish as the ideal limit ($\eta = 0$) is approached.

A local modification to the equilibrium, which is consistent with a finite length theta pinch, is found that stabilizes both modes. This stabilizing perturbation reduces J_θ (the toroidal current) at the field reversed point thus, it appears that the modes are current driven tearing modes.

1980 SHERWOOD THEORY MEETING
Tucson, Arizona - April 23-25, 1980

DISPERSION DIFFERENTIAL EQUATION FOR A STRAIGHT VLASOV-FLUID SCREW PINCH WITH SMALL ION GYRORADIUS*

H. Ralph Lewis
Los Alamos Scientific laboratory
Los Alamos, New Mexico 87545

A dispersion differential equation is derived within the framework of the Vlasov-fluid model for a general, diffuse-profile straight screw pinch under the assumption of small, but finite, ion gyroradius. ω/Ω_{ci} need not be small compared to unity, but ω may not be very close to Ω_{ci} or one of its harmonics. The parallel streaming derivative is included as part of the lowest-order operator in solving the linearized Vlasov equation. A further assumption is that the $E \times B$ drift speed is small compared to the ion thermal speed. No _a priori_ ordering for the right-hand side of the linearized Vlasov equation is assumed. An intended application of the dispersion differential equation is a straight reversed-field pinch.

*This work performed under the auspices of the U.S. Department of Energy.

3B33

PEST2--Ideal MHD Stability in General Toroidal Coordinates*

R. C. Grimm, R. L. Dewar, and J. Manickam
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

Bineau's form of δW,[1] with model kinetic energy normalization,[2] is expressed in a general "straight-field-line" toroidal coordinate system. The coordinate system is constructed straightforwardly using existing numerical techniques.[3] The Galerkin equations for the model normal modes are formed using the mixed finite element - Fourier expansions employed by PEST 1.[4] Results for a variety of coordinates (including PEST, Hamada and equal-arc length systems) for several non-circular tokamak configurations are presented. This version of PEST is useful for the study of large-n, high-β tokamak ballooning modes, for very small aspect ratio compact tori configurations and for configurations with poloidal divertor systems.

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*Work supported by U. S. DoE Contract DE-AC02-76-CN03073.

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3B34

Bremsstrahlung Spectra Associated with Anomalous Electron Thermal Conduction

J.C. Wiley and F.L. Hinton

Fusion Research Center
The University of Texas at Austin
Austin, Texas 78712

Abstract

A steady-state model of the linearized Fokker-Planck equation has been solved numerically for two types of anomalous electron transport. Electron distribution functions which consistently describe both the thermal and runaway regimes and the soft x-ray spectra computed from them are given. The effect of the anomalous transport on the x-ray spectra is compared with the effect of an electric field. Due to the simplicity of the analytic model and significant enhancement of the soft x-ray spectra predicted, this type of calculation provides a useful tool for anaylsis of the anomalous electron transport from observed x-ray spectra.

This work is supported by the U.S. Department of Energy Contract DE-AC05-79ET-53036.

3B35

WHISTLER INSTABILITY IN EBT*

P. N. Guzdar and R. Marchand
Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20742

The Whistler mode can be driven unstable by a temperature anisotropy in a collisionless plasma by conventional inverse electron cyclotron damping. We have developed an axial mode structure integral equation for the Whistler mode by considering a simple box periodic model for the EBT and treating the electron ring as consisting of trapped particles. We find that for $\omega-\Omega e = m\omega_b$ where m is a positive integer and ω_b the bounce frequency for the electrons in the ring, we get new resonances which can destabilize the mode. We have derived both density and temperature threshold conditions for this instability. Detailed analytic and numerical results are presented to demonstrate the relevance of these results to present day EBT experiments.

*Supported by U.S. Department of Energy.

3B36

Tokamak Plasma Heating with Intense Pulsed Ion Beams

Wallace M. Manheimer and Niels K. Winsor
Plasma Physics Division, Naval Research Laboratory, Washington, D.C.

We examine the possibility of heating a tokamak plasma with an intense pulsed ion beam. With present technology, tens of kilojoules of ion beam energy can now be produced with efficiencies of between 40 and 80%, using magnetically insulated diodes, pinched beam diodes and reflex triodes or tetrodes. It is likely that megajoule ion beams will soon be available. An investigation of whether ion beams can be effective in heating tokamak plasmas must focus on three crucial issues: (1) beam injection, (2) confinement and stability, and (3) deposition of beam energy in the plasma.

We shall present three different ways to inject such a beam into a tokamak or similar geometry. All of these methods rely on injection into a tokamak plasma which is not yet fully formed. The first utilizes the E x B drift velocity to inject into a spatially localized plasma which has normal tokamak electron density and carries a normal tokamak current. The second utilizes the decay of the return current to trap the beam in a plasma which fills the tokamak volume, but has a low electron density. The third relies on a pulsed stabilizing vertical field to catch the beam before it drifts out of a full volume, full density plasma which carries no current.

For the problem of confinement and stability, reference is made to previous work.[1,2] It has been shown that toroidal equilibria exist for an ion beam in a plasma background either in a conducting shell or in an imposed vertical field. The stability can be related to the stability of a plasma whose pressure is replaced with the beam kinetic energy density.

To examine the problem of deposition we used a zero dimensional code with models for electron and ion plasma energy losses. In all cases, the beam is injected at t = 0 and no additional power input or current drive is assumed. If the plasma does not achieve ignition, it heats up and then cools down. However we find that ignition appears to be achievable with tokamaks and beams which are now available or envisioned.

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3B37

STABILITY BOUNDARIES FOR LARGE SCALE, HIGH BETA MIRROR MACHINES

Kim Molvig, M.I.T. and L. D. Pealstein, L.L.L.

Mirror stability to quasi-flute modes driven by the ion loss cone distribution is examined. In larger radius devices, the drift cyclotron-loss cone instability can be eliminated, but then some of the infinite medium modes, such as the negative energy Bernstein mode can become a problem. Stable regions at high beta, are bounded at lower radii by drift cone and at higher radii (for fixed aspect ratio) by negative energy. These boundaries can be obtained by some simple physical arguments from the radially local flute-averaged dispersion relation. The analytically obtained curves are in good agreement with the numerical solutions to the local eigenmode equation. The radial eigenmode problem is formulated to determine the validity of the local theory. We find that DCLC is localized at middle radii where the density gradient is maximum, but that the negative energy mode localizes in the center. The implication of this for the stability boundaries is that the local dispersion relations are reasonable approximations, provided they are evaluated at the appropriate radii. Thus the beta appropriate to drift cone is substantially below the maximum beta in the device. This can have a large stabilizing effect at high β. One of the interesting features is that there is now always a stable region at high $\beta_v \gtrsim .6$ for $R_p/\rho_v \gtrsim 60$. A related point is the possible explanation of the observation of central gyrofrequencies for the instabilities in present devices, in particular, reconciling this with the interpretation as DCLC.

Poster Session Desired

POSTER SESSION

THEORETICAL ANALYSIS OF ION CYCLOTRON FLUCTUATIONS IN TOKAMAKS

R. E. Waltz and R. R. Dominguez

General Atomic Company
San Diego, California 92138

ABSTRACT

Moderate wavelength density fluctuations near the ion cyclotron frequency (Ω_i) have been observed in TFR.[1] The spectrum at $k_\perp \simeq 0.5\ \rho_i^{-1}$ has distinct peaks near 1.5 and 2 Ω_i. We use numerical methods developed for the study of drift waves (see, for example, Refs. 2 and 3) to examine these high frequency electrostatic modes in a sheared magnetic field. Modes are found in which the electrons have a fluid behavior analogous to that of the ions in the case of drift waves. Using an x-space analysis in slab geometry, we find that such modes are weakly damped by shear ($\gamma/\omega \simeq -0.005$). We find no linear mechanism for destabilizing these modes in slab or toroidal geometry. Using the methods of Ref. 3, the thermal fluctuation level from these stable modes is found to be too low by a factor of 10^3. A search is in progress to find the unstable modes with kinetic electron behavior suggested in Ref. 1.

Work supported by Department of Energy, Contract De-AT03-76ET51011, GA Project No. 3235.

[1] TFR Group, Phys. Rev. Lett. *41*, 113 (1978).

[2] R. E. Waltz, W. Pfeiffer, R. R. Dominguez, Nucl. Fusion *20*, 43 (1980).

[3] R. E. Waltz, W. Pfeiffer, R. R. Dominguez, General Atomic Company Report GA-A15434 (1979), to be published in Phys. Fluids.

3B39

A DIFFUSING TEST PARTICLE SUPERPOSITION PRINCIPLE FOR ELECTROSTATIC DRIFT WAVE TURBULENCE

Ken Swartz and Kim Molvig
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

A closed system of equations is derived and solved for the statistical functions necessary for calculating the level of electrostatic drift wave turbulence in a sheared magnetic field. The functions required are the one point electron distribution function, and the two-time, two-point functions for electron self-correlation, correlation between two electrons, and correlation between one electron and one ion. The electrons are treated nonlinearly in the stochastic regime. Coarse graining in phase space, which is the same procedure used to renormalize the electron Vlasov equation, can also be used to renormalize the drift-kinetic Klimontovitch equation for the electrons. The ions are described by the linearized Klimontovitch equation. Ion discreteness and higher order ion correlations are neglected. After renormalizing, the Liouville average yields a closed system of equations in which electron discreteness is found to be the only source of fluctuations. This contrasts a recent related calculation.[1] These equations are shown to be equivalent to a diffusing test particle problem, and the fluctuation spectrum is thus expressed as the superposition of diffusing test particles. The test particle problem reduces to the nonlinear drift wave eigenmode problem solved by Hirshman and Molvig.[2] Furthermore, when the spectrum and collision integral are computed, the resulting radial diffusion coefficient differs negligibly from the result of Hirshman and Molvig, thus confirming the validity of the one-point marginal stability calculation.

[1] Hirshman, S.P. and Diamond, P.H., Preprint, ORNL/TM-7093 (1979).

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

Poster Session Desired

3B40

RESISTIVE MHD CALCULATIONS IN MODERATE β TOKAMAKS*

J. A. Holmes, B. Carreras†, W. A. Cooper, H. R. Hicks, V. E. Lynch
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

We consider the tearing mode evolution for moderate β tokamaks ($\beta \sim \varepsilon \equiv a/R$ and $\varepsilon \lesssim .1$). We employ a reduced set of resistive MHD equations valid in this limit, which were derived for ideal MHD by H. Strauss.[1] They are expressed in a non-orthogonal toroidal coordinate system ρ, θ, ζ similar to the one in Ref. 2. The equations are numerically advanced using a Fourier expansion in the θ and ζ angles and finite differences in ρ. The equilibrium is numerically calculated by a flux conserving method. In the limit of large toroidal mode number n this reduced set of equations gives a ballooning mode equation. Results will be presented displaying the dependence of growth rates and mode structure on the toroidal mode number n, the plasma resistivity, and the plasma β.

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†Presently at Institute for Advanced Studies, Princeton, New Jersey.

[1] H. Strauss, Phys. Fluids 20 (1977) 1354.

[2] R. C. Grimm, et al., in Methods of Computational Physics, Vol. 16 (1976) 253.

RELATIVISTIC EFFECTS ON STRONG LANGMUIR TURBULENCE

H. P. Freund
Science Applications, Inc.,
McLean, Va. 22101

C. S. Liu
Department of Physics and Astronomy
University of Maryland,
College Park, Maryland 20742

and

R. M. Kulsrud
Plasma Physics Laboratory,
Princeton University,
Princeton, New Jersey 08540

ABSTRACT

The relativistic effects on strong Langmuir turbulence which arise due to both weakly relativistic plasma temperatures and high amplitude oscillations (i.e., where the oscillatory electron velocity due to the wave approaches the speed of light) are considered. In the case in which relativistic effects arise primarily from high plasma temperature, a kinetic formalism is employed in which a nonlinear Schrödinger equation is derived from expansion of the Vlasov-Maxwell equations. The analysis is appropriate to either hydrogen or electron-positron plasmas, and the relativistic effect is found to provide a nonlinear phase-mixing in three dimensions. A fluid treatment is used when the relativistic effects of high wave amplitudes predominate. In this limit, ion dynamics are unimportant in the initial phases of the interaction and the relativistic electron mass correction is shown to result in the same type of three dimensional phase-mixing found in the kinetic analysis. A Lagrangian formalism appropriate to each limiting case is described which leads to a virial theorem from which thresholds for collapse of arbitrary localized wave packets can be derived.

The Effect of Low Frequency Density Fluctuations on Electron Cyclotron Resonance Heating

B. H. Hui, P. N. Guzdar* and E. Ott*
Naval Research Laboratory, Washington, D.C.

Scattering of externally launched heating wave at electron cyclotron resonance frequency by low frequency density fluctuations is studied. Starting from the wave equation and fluid equations, we derive a function $P(\beta)$ which describes the probability of $\underset{\sim}{k}_\perp$ being scattered by an angle β. A Monte Carlo method is used to incorporate this probability function into the ray tracing code to study the propagation and absorption of the launched wave. Results of heating by ordinary and extraordinary modes on PLT and UWM III will be presented.

* University of Maryland, College Park, Maryland

3B43

POSTER SESSION

IMPROVEMENT OF TOKAMAK PLASMA HEAT CONTAINMENT BY POLOIDALLY ASYMMETRIC HEATING

S. K. Wong and K. H. Burrell

General Atomic Company
San Diego, California 92138

ABSTRACT

There is evidence that ion heat diffusion in tokamaks obeys neoclassical theory. In this theory, the ratio of the ion gyroradius to the plasma inhomogeniety scale length, δ, is small. Rapid motions along the field line relax the plasma to a quasi-steady state in which any initial poloidal asymmetries have been reduced to first order in δ. The cross-fieid fluxes then appear as second order terms. It is thus obvious that poloidally asymmetric external sources strong enough to interfere with the establishment of the quasi-steady state can alter the resultant second order fluxes. Such an effect has been predicted[1] and observed[2] in the impurity flow reversal experiment. Here we examine the effect of asymmetric heat source on the ion heat flux of a pure plasma, in all three regimes of collisionality. We find that the modification of the heat flux in each case can be obtained by making the replacement $n(\partial T_i/\partial r) \rightarrow n(\partial T_i/\partial r) + \xi(eBR)(S/T_i)$ in the usual expression for the heat flux. In this formula, S is the $\sin\theta$ component of the heat source, θ being the poloidal angle, R is the major radius, and ξ is a numerical factor assuming different values in different regimes of collisionality. Basing on this formula, schemes for improving plasma heat containment through asymmetric heating will be discussed.

Work supported by Department of Energy, Contract DE-AT03-76ET51011, GA Project No. 3235.

[1] T. Ohkawa, Kakuyugo Kenkyu *32*, 67 (1974).

[2] K. H. Burrell, *et al.*, Phys. Rev. Lett. *41*, 1382 (1978).

3B44

Finite Larmor Radius Modifications of an MHD Instability

J.L. Schwarzmeier

Courant Institute of Mathematical Sciences

New York University

Abstract

A model for determining the microstability of general Vlasov-hybrid-Maxwell slab equilibria has been presented previously.[1] A particular self-consistent, high β equilibrium is chosen for study, where the ion larmor radius, field gradient scale lengths, and plasma thickness all are comparable. The gross MHD stability of the configuration is determined, and these results are compared to those of the exact Vlasov-hybrid stability analysis.

Work supported by U.S. DOE Contract DE-AC02-76ER0 3077

[1] J.L. Schwarzmeier, Bull. Amer. Phys. Soc., 23, 751 (1978)

poster session

PROGRAM CORRECTIONS

1. Correct author list for paper 2B1:

   Numerical Study of Low Toroidal Mode Number Instability in a Compact Torus

   A. I. Shestakov, D. D. Schnack, and J. Killeen

2. Correct author list for paper 1C9:

   On the Theory of Internal Disruptions in Tokamaks

   H. Welter and D. Biskamp

LATE PROGRAM CHANGES

1. Paper 3B24 has been moved to Paper 2C46
2. Paper 1C26 has been moved to Paper 2C47
3. Paper 1C28 has been moved to Paper 2C48