Annual

CONTROLLED FUSION THEORY CONFERENCE

APRIL 26–28, 1978

Gatlinburg, Tennessee

SPONSORED BY

FUSION ENERGY DIVISION

OAK RIDGE NATIONAL LABORATORY

PROCEEDINGS OF THE ANNUAL CONTROLLED FUSION THEORY CONFERENCE

APRIL 26-28, 1978

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OAK RIDGE NATIONAL LABORATORY

Oak Ridge, Tennessee

1978 ANNUAL CONTROLLED FUSION THEORY CONFERENCE

General Information

All sessions will be held at the Riverside Motor Lodge. The morning oral sessions will be in Whaley Hall; the afternoon (or evening) poster sessions will be in the Pearl Room. Coffee and other refreshments will be available during both the oral and poster sessions.

There will be two consecutive poster sessions each day. On Wednesday and Friday these will be in the afternoon, but on Thursday the poster sessions will be held in the evening. Thursday afternoon is free for impromptu discussions or other activities, including scheduled hikes in the mountains.

The buffet (the cost of which is included in the registration fee) will be held on Wednesday evening. It will be a cookout with entertainment in the National Park, weather permitting. Free buses will leave from the Riverside Motor Lodge at 5:30 p.m. Guest tickets for adults and children will be available at the registration desk Wednesday morning.

Registration will be open in the lobby of the Riverside Motor Lodge from 4:00-10:00 p.m. on Tuesday, April 25 and beginning at 8:00 a.m. on April 26.

Please check the bulletin board and registration desk for tour and restaurant information. If you wish to participate in one of the scheduled activities Thursday afternoon, please sign up for transportation at the registration desk.

Note from the Chairman of the Selection Committee for Oral Presentations

The committee was presented with the difficult task of selecting 30 papers out of the 210 or so submitted which warranted oral presentations. Considerations which entered the frequently very spirited discussions were:

- Good physics, new, interesting, germane, credible, ...
- Questionable physics which might need to be aired for purposes of pointing out potentially fatal flaws
- New insights or procedures meriting broad discussion
- Balance among competing groupings
- Weariness after attempting to assimilate the sense or importance of contributions when the abstract did not always present prima facie evidence

We left wishing that the other 30 or so papers from the list compiled on the first two rounds of nominations could also be included. However, time availability prevailed and many excellent contributions were judged able to represent themselves adequately in the poster sessions.

It is urged that you communicate to the Sherwood governing board your feelings on how the meeting and the paper selection might be improved in the future. Please fill out and return the questionnaire on this subject which will be available at the meeting.

R. A. Dory
For the Committee

1978 ANNUAL CONTROLLED FUSION THEORY CONFERENCE

Schedule

WEDNESDAY, APRIL 26

8:30 a.m.	Welcome and announcements, D. Nelson
8:40 a.m.	Oral session
10:20-10:40 a.m.	Coffee break
12:30 p.m.	Lunch
1:45-3:15 p.m.	Poster session A
	Coffee served 2:15-4:15 p.m.
3:30-5:00 p.m.	Poster session B
5:30 p.m.	Buses leave for cookout

THURSDAY, APRIL 27

8:40 a.m.	Oral session
10:20-10:40 a.m.	Coffee break
12:30 p.m.	Lunch
1:45 p.m.	Buses leave for mountains
7:30-9:00 p.m.	Poster session C
	Coffee served 8:00-10:00 p.m.
9:00-10:30 p.m.	Poster session D

FRIDAY, APRIL 28

8:40 a.m.	Oral session
10:20-10:40 a.m.	Coffee break
12:30 p.m.	Lunch
1:45-3:15 p.m.	Poster session E
	Coffee served 2:00-3:00 p.m.

PROGRAM

1978 ANNUAL CONTROLLED FUSION THEORY CONFERENCE

WEDNESDAY, APRIL 26

8:30 AM WELCOME AND ANNOUNCEMENTS D. B. NELSON, ORNL

8:40 AM ORAL SESSION D. Baldwin and J. Brackbill, Chairmen

CA1 G. O. Spies, "Asymptotic Theory of Diffuse High Beta Magnetohydrostatic Equilibria in Three Dimensions"

OA2 T. H. Jensen and R. L. Miller, "Low Frequency Heating of Doublets"

CA3 A. Hasegawa, "Stabilization of Drift Cyclotron Loss-Cone Mode by Low Frequency Density Fluctuations"

OA4 J. W. Connor, R. J. Hastie, A. Sykes, and J. B. Taylor "High Mode Number Stability of Axisymmetric Plasma"

OA5 B. I. Cohen, N. Maron, and T. D. Rognlien, "A Local Theory of Nonlinear Ion Dynamics in a Drift-Cyclotron Mode"

10:20 - 10:40 AM COFFEE BREAK

CA6 H. R. Strauss, R. D. Hazeltine, S. M. Mahajan, and D. W. Ross, "Twisting Modes"

OA7 C. E. Seyler, Jr., and J. P. Freidberg, "The Nonexistence of Absolute Finite Larmor Radius Stabilization"

OA8 L. Turner, D. C. Barnes, and D. Montegomery, "Statistical Equilibria of Nonlinear Continuum Mechanics"

CA9 L. Chen, P. N. Guzdar, R. B. White, P. K. Kaw, and C. Oberman, "Theory of Universal Drift-Wave Eigenmodes in a Sheared Magnetic Field"

OA10 H. H. Klein, M. Cotsaftis, N. A. Krall, and J. B. McBride, "Dynamics of Trapped Electron Instability Dominated Tokamak Discharges"

12:30 PM LUNCH

POSTER SESSION A
(1:45-3:15 PM)

A1 S. K. Wong and K. H. Burrell, "Poloidal Asymmetry of Impurity Ion Distribution in Tokamaks"

A2 C. Chu, M-S. Chu, J-Y. Hsu, and T. Ohkawa, "Interaction of Current Filaments in a Magnetic Field"

A3 G. J. Morales, "Energy Clamping of Runaway Electrons"

A4 R. C. Myer and A. Simon, "Threshold Saturation of the Drift Cyclotron Loss Cone Instability"

A5 J. D. Gaffey, Jr., and R. S. Schneider, "Alpha Particle Collisional Transport in Thermonuclear Plasma"

A6 I. R. Lindemuth and M. M. Widner, "Numerical Computation of Plasma Behavior in Relativistic Electron Beam Targets"

A7 W. M. Stacey, Jr., "Source Effects Upon Collisional Transport in Tokamaks"

A8 C. D. Boley, E. M. Gelbard, and S. P. Hirshman, "On the Transport of Ions with Multiple Charge States in Neoclassical Theory"

A9 N. Byrne and M. Cotsaftis, "Effect of TEM on Oxygen in Tokamaks"

A10 R. H. Cohen, D. V. Anderson, and C. Sharp, "Orbital Resonances in Quadrupole- Stabilized Mirror Configurations"

A11 D. C. Watson and T. D. Rognlien, "Spatial Eigenmodes for the Alfven-Ion-Cyclotron Instability in Finite-Length Plasma"

A12 R. H. Cohen, "Time-Dependent Tandem Mirror Confinement Studies"

A13 G. Conn and J. A. Tataronis, "Perturbation of the Alfven Continuum by the Hall Effect"

A14 R. Kashuba, T. Kammash, and H. H. Fleischmann, "Streaming Instabilities in a Plasma With Electron or Ion Rings"

A15 V. S. Chan and S. C. Chiu, "Theoretical Interpretation of Nonlinear RF Coupling In Recent General Atomic Lower Hybrid Heating Experiments"

A16 R. W. Moore, L. C. Bernard, D. Dobrott, and F. J. Helton, "Comparison of Global and Local Stability Analyses of the Ballooning Mode"

A17 K. R. Chu and A. T. Drobot, "Efficient High Power Gyrotron Travelling Wave Amplifier - Theory and Simulation"

A18 A. Aydemir and C. K. Chu, "Mangetohydrodynamic Simulation of Plasma Formation in TORMAC"

A19 F. L. Hinton, "Nonlinear Electric Field-Driven Transport in Tokamaks"

A20 R. D. Hazeltine, H. R. Strauss, S. M. Mahajan, and D. W. Ross, "Variational Methods for Electromagnetic Instabilities"

A21 J. T. Woo, "Toroidal Fusion Energy Amplifier Vs. Ignition Reactor"

A22 J. Johner and E. K. Maschke, "Shear Damping of Drift Modes in the Presence of a Strong Shear and a Periodic Gravity"

A23 O. Betancourt, P. Garabedian, and F. Herrnegger, "Influence of D-shaped Plasma Cross Sections on m = 1 and m = 2 Modes"

A24 B. N. A. Lamborn, "Nonlinear Propagation of Electrostatic Pulses"

A25 D. Schnack and J. Killeen, "Nonlinear Evolution of Resistive Interchange Modes in a Reversed Field Pinch"

A26 Y. Satya and G. Schmidt, "Interaction of Tearing Modes"

A27 K. Evans, Jr., "Optimization of the F(psi) Profile in Tokamak MHD Equilibrium Calculations"

A28 E. C. Morse and G. H. Miley, "Stability in the Field-Reversed Mirror"

A29 H. Tesser and B. Rosen, "Automated Calculation of Parametric Processes in Vlasov Theory"

A30 S. Hamasaki and N. A. Krall, "Modeling of High-Beta Plasma Diffusion Due to Low Frequency Microinstability"

A31 P. McKenty, R. Morse and G. Sowers, "Modeling of SCYLLA IV-P End Plug Experiments"

A32 J. M. Finn, "Ergodic Behavior of Beam Orbits in Field Reversed Ion Rings"

A33 M. J. Gerver and R. N. Sudan, "Beam-Driven Instabilities in a Field-Reversed Ion Layer"

A34 E. Hameiri, "Shear Stabilization of the Rayleigh-Taylor Modes"

A35 R. G. Kleva, J. A. Krommes, and C. Oberman, "Electron Heat Transport in Stochastic Magnetic Fields"

A36 E. A. Adler and R. M. Kulsrud, "Energy in the Linear Tearing Mode"

A37 S. P. Hirshman and A. H. Boozer, "Parallel Equilibrium Current in a Toroidal Plasma"

A38 B. Carreras, H. R. Hicks, J. A. Holmes, D. K. Lee, S. J. Lynch, and B. V. Waddell, "Status of Nonlinear Resistive MHD Research at Oak Ridge National Laboratory"

POSTER SESSION B
(3:30-5:00 PM)

B1 J. M. Rawls and R. W. Harvey, "Analytic Computation of Minimum Beta at Ignition For Various Transport Scaling Laws"

B2 R. W. Harvey, "Coupling of Single WaveGuide Radiation to Plasma Whistler and Lower Hybrid Modes"

B3 J. B. McBride, S. Hamasaki, and N. A. Krall, "Stability Theory at Intermediate Frequency in Fusion Systems"

B4 N. A. Krall, J. B. McBride, and A. L. Sulton, Jr., "Neoclassical Model of Particle and Energy Balance for EBT"

B5 D. E. Baldwin and M. E. Rensink, "Electron Effects in Ion-Current Field Reversal"

B6 T. B. Kaiser, "Neutral Particle Transport in Mirror Machines: Monte Carlo Simulation"

B7 T. Mizoguchi, T. Kammash, and D. J. Sigmar, "Effect of Ellipticity on MHD Equilibria of Flux-Conserving Tokamaks"

B8 D. L. Galbraith and T. Kammash, "Multispecie Confinement in Tandem Mirror Reactors"

B9 S. C. Chiu and V. S. Chan, "Nonlinear Wave-Plasma Coupling at the Lower Hybrid Frequency"

B10 R. L. Miller, "Transport in Doublets"

B11 M. S. Chu, C. Chu, G. Guest, J. Y. Hsu, R. Moore, and T. Ohkawa, "Kinetic Description of MHD Ballooning Mode in Tokamaks with General Cross Section"

B12 H. C. Lui, "Induction of Force-Free Currents by Boundary Displacements in a Screw Pinch"

B13 R. N. Byrne and C. K. Chu, "Transport and Radiation Studies of Belt Pinches and High Beta Tokamaks"

B14 W. Horton, Jr., D. A. Hitchcock, and S. H. Brecht, "Spatial Structure of the Beam Driven Mode at Twice Ion Gyro Frequency"

B15 S. M. Mahajan and D. W. Ross, "Localized Trapped Electron Drift Instability"

B16 J. C. Wiley and F. L. Hinton, "Numerical Calculation of Impurity Diffusion in Tokamaks"

B17 J. Y. Choe and R. C. Davidson, "Internal Kink Instabilities in Reversed Field Pinches"

B18 M. Tagger and R. Pellat, "A Kinetic Study of Nonlinear Saturation of Trapped Ion Modes By Mode Coupling"

B19 V. Krapchev and A. Bers, "Kinetic Approach to the Pondermotive Effects in a Plasma"

B20 N. T. Gladd, J. D. Huba, and R. C. Davidson, "Lower-Hybrid-Drift Instability in Linear Fusion Systems with Reversed Magnetic Fields"

B21 P. H. Ng, N. T. Gladd, and C. S. Liu, "Warm Plasma Effects on the DCLC Mode"

B22 V. K. Tripathi and C. S. Liu, "Saturation of Parametric Decay of Lower Hybrid Waves Into Ion Cyclotron Waves in Inhomogeneous Plasmas"

B23 N. J. Fisch, "Continuous Operation of Tokamak Reactors with RF-Driven Currents"

B24 K. Audenaerde, G. Emmert, and M. Gordinier, "SPUDNUT - A Fast Neutral Transport Routine"

B25 H. L. Berk, W. M. Sharp, and N. T. Gladd, "Effect of Shear on DCLC Mode"

B26 M. C. Vella, H. L. Berk, and S. Hamasaki, "Numerical Modeling of Plasma Heating in TORMAC"

B27 V. K. Decyk, G. J. Morales, and J. M. Dawson, "Simulation of Lower Hybrid Heating of a Nonuniform Plasma"

B28 D. W. Hewett and A. G. Sgro, "Zero Electron Mass Plasma Simulation in Two Dimensions"

B29 J. U. Brackbill, "Numerical Simulation of the Tormac Experiment"

B30 H. R. Lewis, "Magnetoacoustic Heating of a Collisionless Pinch"

B31 M. H. Emery, J. Gardner, M. Fritts, J. Boris, and N. Winsor, "A General Two-Dimensional Tokamak Model"

B32 J. M. Finn and R. N. Sudan, "Resonant Instabilities of a Field-Reversed Ion Ring"

B33 M. J. Gerver and R. N. Sudan, "Beam-Driven Instabilities in a Field-Reversed Ion Layer"

B34 M. J. Gerver, "High Frequency Convective Loss-Cone Instability in Short Mirror Machines"

B35 E. Hameiri, "An Exactly Soluble Model For Reconnection"

B36 R. B. White, D. A. Monticello, and M. N. Rosenbluth, "Feedback Stabilization of Tearing Modes in Tokamaks"

B37 Y-K. M. Peng, "Continuous Tokamaks"

THURSDAY, APRIL 27

8:40 AM ORAL SESSION F. Hinton and G. Morales, Chairmen

OB1 M. S. Chance, R. L. Dewar, E. A. Frieman, A. H. Glasser, J. M. Greene, Y-Y. Hsieh, J. L. Johnson, J. Manickam, and A. Todd, "Radial Structure of Ballooning Modes"

OB2 S. C. Jardin, S. P. Hirshman, and J. L. Johnson, "Two Dimensional Transport of Tokamak Plasmas"

OB3 J. A. Krommes, R. G. Kleva, and C. Oberman, "Stochasticity, Turbulence, and Anomalous Transport"

OB4 C. Z. Cheng and H. Okuda, "Theory and Simulations of Trapped-Electron Instabilities"

OB5 J. F. Drake, P. L. Pritchett, and Y. C. Lee, "Nonlinear Evolution of Tearing Instabilities: Violations of Constant Psi-Star"

10:20 - 10:40 AM COFFEE BREAK

OB6 A. T. Lin, H. Okuda, J. M. Dawson, and C. C. Lin, "Thermal Magnetic Fluctuations and Anomalous Diffusion"

OB7 E. Ott, K. R. Chu, and B. Hui, "Theory of the Production and Use of RF for Tokamak Plasma Heating in the Electron Cyclotron Frequency Range"

OB8 H. Weitzner, "Effects of Multipole Fields on the Stability of High Beta Mirrors"

OB9 A. N. Kaufman, S. W. McDonald, N. R. Pereira, and N. Pomphrey, "Ray Trajectories and Eigenvalue Spectra of Nonseparable Field Equations"

OB10 T. Antonsen, Jr., B. Coppi, and R. Englade, "Anomalous Inward Transport and Density Rise in Magnetically Confined Plasmas"

12:30 PM LUNCH

POSTER SESSION C
(7:30-9:00 PM)

C1 W. C. Condit, R. P. Freis, R. M. Glaser, T. B. Kaiser, S. L. Rompel, and J. A. Byers, "Simulation Models for Effect of RF turbulence on 2XIIB"

C2 B. McNamara, "Simple Rotating Field Reversed Plasma Equilibria"

C3 G. R. Smith, J. A. Byers, and L. L. Lodestro, "Superadiabatic Ion Motion in the Presence of an Electrostatic Wave in a Mirror Machine"

C4 T. D. Rognlien, "Monte Carlo Calculation of Electron Heat Flow For the Transition From Collisional To Collisionless Regimes"

C5 R. E. Waltz and W. W. Pfeiffer, "Tokamak Empirical Scaling Laws and the Multiregime Trapped Electron Modes"

C6 L. C. Bernard, D. Dobrott, F. J. Helton, and R. W. Moore, "The Localized Interchange And Internal Ballooning Mode Stability"

C7 D. Choi, J. Wiley, R. Estes, and W. Horton, "Numerical Investigation of the Two Dimensional Fokker Planck and Quasilinear Equations"

C8 D. W. Ross, R. D. Hazeltine, F. L. Hinton, S. M. Mahajan, W. H. Miner, and H. R. Strauss, "Numerical Methods for Electromagnetic Instabilities"

C9 K. D. Marx, R. W. Harvey and J. M. Rawls, "Fokker Planck Studies of Plasma Heating and Current Generation Due to RF Induced Quasilinear Diffusion"

C10 A. A. Mirin and D. L. Jassby, "Fokker Planck/Transport studies of the PDX, PLT and TFTR Incorporating a Self Consistent Neutrals Treatment"

C11 W. B. Downum, G. H. Miley and C. K. Choi, "Buildup of Alpha-Particle Impurities in a Fusion Toroidal Plasma

C12 B. Rosen, "Constants of Motions and Higher Order Resonances"

C13 R. Morse, P. McKenty and G. Sowers, "Axial Heating of Linear Magnetic Fusion Systems"

C14 A. Sen, "Lower Hybrid Wave Propagation in a Turbulent Plasma"

C15 R. A. Gerwin and R. W. Moses, Jr., "Fast Liner Scaling"

C16 R. Y. Dagazian, "The Effect of Convection on the Stability of the Plane Magnetized Plasma Slab"

C17 T. E. Cayton and J. P. Freidberg, "Finite Larmor Radius Stabilization of m = 1 Kink Modes in a Screw Pinch"

C18 N. K. Winsor, W. H. Miner, and I. B. Bernstein, "A Numerical Model for Electron Dynamics in Tokamaks"

C19 B. H. Hui, D. L. Book, and P. C. Liewer, "Modeling of a Reversed-Field Configuration With a 1-D Quasiequilibrium Code"

C20 G. Vahala, "Cylindrical, Axially Symmetric MHD Turbulence"

C21 A. B. Hassam and R. M. Kulsrud, "Effect of Diamagnetic Currents on Drift Waves in Toroidal Geometry"

C22 R. Marchand, G. Rewoldt, W. M. Tang, and W. H. Miner, "Two Dimensional Structure of the Trapped Ion Instability"

C23 D. Monticello, R. White, and M. N. Rosenbluth, "Rotating Magnetic Islands"

C24 C. F. F. Karney and F. W. Perkins, "Alfven Heating Via Magnetosonic Modes in Large Tokamaks"

C25 R. A. Hulse, D. E. Post, and C. B. Tarter, "A Coronal Atomic Physics Algorithm for Low and High Z Impurities"

C26 R. S. Devoto, D. R. Faul, and B. W. Stallard, "Simulation of 2XIIB Experiments With A Guiding Center Code"

C27 D. A. D'Ippolito, J. F. Drake and Y. C. Lee, "Stability of High-m Tearing Modes"

C28 R. N. Sudan and M. N. Rosenbluth, "Stability of Axisymmetric Field-Reversed Equilibria of Arbitrary Ion Gyro-Radius"

C29 W. M. Sharp and H. E. Mynick, "Strongly Inhomogeneous Valsov Slab Equilibria"

C30 L. Steinhauer, "Cross-Field Transport of a High-Beta Plasma"

C31 D. Kelley, Y. C. Lee, A. Banos, and B. D. Fried, "Nonlocal Theory of Drift Waves"

C32 B. Coppi, A. Ferreira, J. Filreis, J. W-K. Mark, and J. Ramos, "Physical Properties of "Disconnected" Ballooning Modes"

C33 B. Coppi, J. W-K. Mark, L. Sugiyama, and G. Bertin, "Stabilization of the "Reconnecting" and Tearing Modes in the Collisionless Regime"

C34 C. S. Liu and J. R. Myra, "Nonlinear Propagation of Ion Cyclotron Waves in a Homogeneous Plasma"

C35 C. Grebogi, C. S. Liu, and V. K. Tripathi, "The Effects of Ion Nonlinearity on the Parametric Decay of Lower Hybrid Waves of Finite Propagation Vector in A Plasma"

C36 W. M. Tang, R. B. White, and P. N. Guzday, "Impurity Driven Drift Eigenmodes in a Sheared Magnetic Field"

C37 S. P. Auerbach and A. H. Boozer, "The Effects of Viscosity on Classical Diffusion Near an X-Point"

C38 J. T. Hogan, "MHD/Transport Effects on Tokamak Confinement Scaling"

POSTER SESSION D
(9:00-10:30 PM)

D1 J-Y. Hsu, M-S. Chu, and C. Chu, "Density Flattening and Quasilinear Evolution of Individual Micromagnetic Cells"

D2 M. G. McCoy, M. E. Rensink, A. A. Mirin, J. Killeen, "The Role of Equilbria In Noncircular Transport Calculations"

D3 D. E. Driemeyer, G. H. Miley, M. Y. Wang, and W. C. Condit, "Fusion Product Heating of Field-Reversed Mirrors"

D4 N. T. Gladd and C. S. Liu, "Current Driven Drift Waves and Trapped Electron Modes in Sheared Magnetic Field"

D5 N. T. Gladd and J. D. Huba, "Finite Beta Effects on the Ion-Cyclotron-Drift Instability"

D6 P. C. Liewer and C. S. Liu, "A Unified Approach to Ballooning and Trapped Particle Instabilities"

D7 Y. Mok and C. S. Liu, "Theory of Nonthermal Radiation at Electron Plasma Frequency From Tokamaks"

D8 L. Turner, "Rigid-Drift Magnetohydrodynamic Equilibria for Cylindrical Pinches"

D9 D. Winske, "Simulation of a High Frequency Loss Cone Instability"

D10 S. P. Gary and A. G. Sgro, "Electrostatic Heat Flux Instabilities and the Reduction of Axial Thermal Loss"

D11 D. Montgomery, G. Vahala, and L. Turner, "Most Probable States in Magnetohydrodynamics"

D12 D. Mikkelsen and D. Post, "Calculations of Alpha Particle Heating in Tokamaks"

D13 M. A. Mostrom and A. H. Boozer, "Annihilation Model of the Tormac Sheath"

D14 R. L. Dewar, "Hamilton's Principle for a Hydromagnetic Fluid with a Free Boundary"

D15 L. Chen, P. N. Guzdar, J. Y.Hsu, P. K. Kaw, C. Oberman and R. White, "Theory Of Dissipative Drift Instabilities in Sheared Magnetic Field"

D16 J. Hsu, L. Chen, and P. K. Kaw, "Resistive Drift and Alfven Instabilities in Sheared Magnetic Fields"

D17 A. Mankofsky, A. Friedman, and R. N. Sudan, "Numerical Study of Strong Ion Ring Trapping Efficiency"

D18 A. Friedman, R. N. Sudan, and J. Denavit, "A Linearized 3-D Hybrid Code for Stability Studies of Axisymmetric Field-Reversed Equilibria'

D19 H. E. Mynick, "Finite Gyroradius Guiding Center Hamiltonian"

D20 D. A. Larrabee, R. V. Lovelace, and H. H. Fleischmann, "Equilibria and Compression Of Ion Rings"

D21 R. Englade, T. Antonsen, and B. Coppi, "Numerical Modeling of Inward Transport In Magnetically Confined Plasmas"

D22 T. Tajima and J. M. Dawson, "Ion Cyclotron Resonance Heating Through the Slow Waves: A Simulation Study"

D23 S. Johnston and A. N. Kaufman, "Induced Scattering By Oscillation Centers in Nonuniform Plasma"

D24 C. E. Singer, L. Bromberg, J. Hovey, and D. L. Jassby, "Neutral-Beam Driven Currents In Tokamaks"

D25 E. F. Jaeger, D. A. Spong, and C. L. Hedrick, "Neoclassical Transport in the Elmo Bumpy Torus"

D26 L. W. Owen, R. A. Dandl, and C. L. Hedrick, "Calculated Effects of Aspect Ratio Enhancement on Particle Confinement in EBT"

D27 J. D. Callen and C. L. Hedrick, Jr., "Direct Particle Losses in the Elmo Bumpy Torus (EBT)"

D28 C. L. Hedrick, D. A. Spong, and E. F. Jaeger, "Banana Transport in EBT"

D29 A. Cooper, G. Bateman, D. B. Nelson, and T. Kammash, "Effect of Tensor Pressure On Tokamak Equilibrium and Stability"

D30 W. I. van Rij, H. K. Meier, C. O. Beasley, Jr., and J. E. McCune, "Numerical Study of Drift Mode Behavior Using a Self-Consistent Drift-Kinetic Expansion"

D31 C. E Wagner, "Pre-ignition Plasma Studies of Small High-Field Ohmically Heated Tokamaks"

D32 R. W. Huff, C. C. Wu, and J. M. Dawson, "Large-Scale Plasma Simulation on the Chi Computer"

D33 E. Ott, J.-M. Wersinger, and P. T. Bonoli, "Toroidal Effects on Lower Hybrid Wave Propagation"

D34 R. E. Aamodt, Y. C. Lee, C. S. Liu, D. R. Nicholson, M. N. Rosenbluth, H. H. Chen, and D. Chernin, "Nonlinear Theory of Drift Cyclotron Modes in Mirror Machines"

D35 J. L. Eddleman, C. W. Hartman, J. W. Shearer, and W. C. Turner, "Applications of Plasma Guns to Produce Field Reversal"

D36 D. Quimby, A. Hoffman, and L. Steinhauer, "Quasi-Steady Modelling of Laser Heated Plasma Columns"

D37 R. Morse, P. McKenty, and G. Sowers, "Axial Heating of Linear Magnetic Fusion Systems"

D38 D. C. Stevens, E. Turkel, S. Wollman, W. Grossman, and H. Grad, "Numerical Simultion of Reversed Field Buildup in a Mirror Machine"

FRIDAY, APRIL 28

8:40 AM ORAL SESSION E. Ott and J. Tateronis, Chairmen

OC1 K. Lackner, "Temperature Stabilization in a Tokamak Reactor by Control of the Plasma Position"

OC2 R. V. Lovelace, "Kinetic Theory of Ion Ring Compression"

OC3 T. Antonsen, Jr., "On the Stability of Bound Eigenmode Solutions for the Collisionless Universal Instability"

OC4 Y. C. Lee and J. W. VanDam, "Kientic Theory Of Ballooning Instabilities"

OC5 J. L. Shohet, "Enhanced Transport in Low Frequency Heating of Magnetically Confined Plasmas by Island Formation"

10:20 - 10:40 AM COFFEE BREAK

OC6 D. B. Batchelor and C. L. Hedrick, "Investigation of Trapped-Particle Instabilities in EBT"

OC7 K. T. Tsang, J. C. Whitson, J. D. Callen, P. J. Catto, and J. Smith, "Drift-Alfven Waves in Tokamaks"

OC8 M. N. Bussac, M. N. Rosenbluth, and H. P. Furth, "Macroscopic Stability of the Spheromak"

OC9 Y. Pao and P. Rosenau, "Nonlinear MHD Modes and Bifurcation"

OC10 H. Grad, W. Grossmann, D. C. Stevens, E. Turkel, S. Wollman, "Macroscopic Transport Model For a Reversed Field Mirror Machine"

12:30 PM LUNCH

POSTER SESSION E
(1:45-3:15 PM)

E1 M. Campbell and G. H. Miley, "A Treatment for Plasma Buildup in a Small Mirror Fusion Device"

E2 J. Busnardo-Neto, P. C. Liewer, and A. G. Sgro, "Hybrid Model Simulation of Thor"

E3 F. L. Cochran and P. C. Liewer, "Numerical Studies of Nonlinear MHD Properties of A Finite-Beta Plasma and Comparison with Experiment"

E4 H. S. Uhm and R. C. Davidson, "Hybrid Stability Properties of a Cylindrical Rotating P-Layer Immersed in a Uniform Background Plasma"

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E18 W. A. Houlberg, S. L. Milora, C. A. Foster, H. C. Howe, and M. A. Iskra, "Pellet Injection Model and Comparison with ISX"

E19 G. Conn, J. A. Tataronis, "Perturbation of the Alfven Wave Continuum by the Hall Effect"

E20 M. Soler and J. D. Callen, "Heat Transport in Tokamaks as Observed from Sawtooth Oscillation Characteristics"

E21 K. Molvig and D. J. Sigmar, "Anomalous Slowing Down of Alpha Particles in Toroidal Plasma"

E22 B. V. Waddell, B. Carreras, and H.R. Hicks, "Poloidal Magnetic Field Fluctuations in Tokamaks"

E23 H. R. Hicks, B. Carreras, J. A. Holmes, D. K. Lee, S. J. Lynch, and B. V. Waddell, "Major Disruptions in Tokamaks: T-4 and PLT"

E24 S. J. Lynch, B. Carreras, H. R. Hicks, J. A. Holmes, D. K. Lee, and B. V. Waddell, "Generation of Large Magnetic Islands in the Single Pitch Approximation"

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E26 J. R. Cary and J. H. Hammer, "Enhanced Mirror Confinement Due to MHD Oscillations"

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E28 P. J. Channell, "Equilibria for Field-Reversing Rings"

E29 E. Turkel and W. Grossmann, "High Order Methods for Nonlinear Time Dependent MHD"

E30 P. Rosenau and Y-P. Pao, "Scaling and Similarity Laws for Plasma Confinement'

E31 P. N. Hu, "Nonlinear Stability Problems on Two Time Scales"

E32 M. Schmidt, "The Stabilizing Effects of Pressure Anisotropy"

E33 A. M. M. Todd, J. Manickam, M. S. Chance, R. C. Grimm, J. M. Greene, and J. L. Johnson, "Effect of Current Profiles on MHD Stability Limits in Tokamaks"

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E36 S. P. Hirshman and E. C. Crume, "Collisionality Dependence of the Pfirsch-Schluter

E37 W. Horton, "Drift Mode Stability Analysis for TMS" Contribution to Neoclassical Diffusion"

Asymptotic Theory of Diffuse High Beta Magnetohydrostatic Equilibria in Three Dimensions

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To demonstrate the possibility of asymptotically constructing diffuse high beta magnetohydrostatic equilibria as solutions of a boundary value problem in arbitrary toroidal domains, an asymptotic equilibrium theory is developed for large aspect ratio and small deviations from axial symmetry with many toroidal periods (old Scyllac scaling). Given two arbitrary profiles (e.g., the pressure ratio β and the rotation number μ as functions of the volume), and given (within the scaling) an arbitrary boundary at which the magnetic field is required to be tangential, there is a formal power series solution of the magnetohydrostatic equations. To leading order, this solution is obtained from a coupled set of quasi-linear elliptic equations in two dimensions. Iteration schemes are described for solving this set numerically. The details depend crucially on how β and μ are scaled. The lowest order pressure surfaces depend on the corrugation of the boundary for high β, but not for low β (in the latter case, the lowest order problem reduces to the well-known equilibrium equation in two dimensions). For high β and large μ the pressure is always constant at the boundary to leading order, while for high β and finite μ the lowest order pressure surfaces in general intersect the boundary, thus causing a high current boundary layer unless μ vanishes in all orders. As a consequence, the corrugation of the wall must be judiciously chosen in high beta stellarators. The present investigation opens up a new theoretical approach to a variety of high beta magnetic confinement problems in three dimensions, such as plasma heating, stability, adiabatic compression and diffusion.

LOW FREQUENCY HEATING OF DOUBLETS*

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ABSTRACT

Previous analysis[1] of axisymmetric, low-frequency modes of doublets showed the importance of including finite plasma resistivity in an MHD modeling of the problem. One of the modes (quadrupole-like) is particularly interesting in that it has associated with it a large perturbed current density close to the separatrix of the equilibrium. Driving this mode by external coils is a method of heating the plasma. Two approximations, valid in the limits of small and large resistivities, respectively, have been used to calculate the heating in order to assess the usefulness of the method. The formulation[1] of the problem is such that solution of a complex integro-differential equation is required. For the high resistivity case an expansion can be made from the infinite resistivity limit (where the integro-differential equation is not complex) which was studied earlier.[2] In this approximation, the heating power (for fixed driving current) is proportional to the frequency squared and inversely proportional to the resistivity. In the limit of vanishing resistivity, resistivity becomes important only close to the separatrix, and the problem again can be solved. In this limit, the heating power is proportional to the frequency and independent of the plasma resistivity. A quantitative assessment of this heating method shows its attractiveness. The method discussed is similar to heating methods[3,4] proposed for single axis tokamaks, but differs in that for the doublet case, axisymmetry is preserved, while for the single axis tokamaks, helical modes are utilized which open the possibility that enhanced transport may accompany the heating.

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STABILIZATION OF DRIFT CYCLOTRON LOSS-CONE MODE BY LOW FREQUENCY DENSITY FLUCTUATIONS

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ABSTRACT

Low frequency ($\omega << \omega_{ci}$) density fluctuations, $\tilde{n}_L$, (which may be produced by the drift wave instability of the cold ion species) can stabilize the drift cyclotron loss-cone (DCLC) mode by scattering electrons and thereby providing anomalous high frequency resistivity to the DCLC mode. $\tilde{E}\times\tilde{B}$ drift of electrons provide the large coupling between the two modes. If the low frequency mode is assumed to be due to the drift wave instability of the cold ions, the critical density fluctuation of the low frequency mode for the stabilization is given by

$$\left| \frac{\tilde{n}_L}{n_0} \right|^2 \gtrsim 4 \frac{T_{ic}}{T_e} \frac{1}{(k_H \rho_i)^3} ,$$

where n_0 is the total plasma density, T_{ic} and T_e are the cold ion and electron temperature, k_H is the wave number of the DCLC mode and ρ_i is the gyroradius of the hot ion.

HIGH MODE NUMBER STABILITY OF AXISYMMETRIC PLASMA

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In order to study stability of high mode number oscillations of a toroidal plasma one must reconcile the long parallel and short perpendicular wavelength of the most dangerous modes with the requirement of periodicity in a sheared magnetic field. This is achieved by a transformation[1] which converts the eigenvalue problem to one in an infinite domain y without periodicity constraints. Then, and only then, one can introduce an eikonal $F \exp(-in \int^{y} \nu \, dy)$, where $\oint \nu \, dy \equiv 2\pi q$, in which the short wavelength variation is entirely contained in the exponential factor and F varies slowly.

The existence of two distinct length scales then forms the basis for a systematic minimisation of the energy functional $\delta W(\xi,\xi)$, and for the calculation of F. In lowest order in $1/n$ the oscillations of each surface are decoupled and a "local" eigenvalue $\omega^2(\psi)$ is determined by an ordinary differential equation in the extended poloidal coordinate y $(-\infty < y < \infty)$. The flux surface coordinate ψ appears only as a parameter and this equation does not determine the structure of the mode in the "radial" ψ coordinate. [But the behaviour of its solution $|y| \to \infty$ reveals an interesting connection with the Mercier stability criterion.]

In higher order a second eigenvalue equation is obtained, this time in the coordinate ψ alone. This determines the radial structure of the mode and relates the local eigenvalue $\omega^2(\psi)$ to the true eigenvalue Ω^2. It shows that modes are localised near the surface where $\omega^2(\psi)$ has its smallest value ω_0^2 and that the true eigenvalue Ω^2 is approximately ω_0^2. Consequently, stability of an axisymmetric plasma can usually be determined from the lowest order theory alone.

Some applications of this theory to JET and other devices will be given.

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A LOCAL THEORY OF NONLINEAR ION DYNAMICS IN A DRIFT-CYCLOTRON MODE*

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The interaction of the ion diamagnetic-drift wave with an ion Bernstein wave can lead to the well-known drift-cyclotron instability. In mirror machines, the drift-cyclotron mode becomes important because it can persist as a residual instability after electrostatic turbulence, as the result of the drift-cone mode, and externally introduced streaming plasma have partially filled the loss cone in velocity space.[1] Local theory[2,3,4] has suggested that nonlinear ion dynamics induced by a single wave can stabilize the drift-cyclotron mode by disrupting the necessary frequency synchronization between the mode frequency ω, the nearest cyclotron harmonic $N\omega_{ci}$, and the ion diamagnetic frequency ω_*. We consider three particular regimes: near linear marginal stability $\omega \approx N\omega_{ci} \approx \omega_*/2$,[2] near the simultaneous resonance $\omega \approx N\omega_{ci} \approx \omega_*$,[3] and in the regime of ion trapping.[4] We review the theories of the stabilization due to a nonlinear frequency shift[2,3] within our own analytical framework and find significant discrepancies. To confirm theoretical predictions and further understand the role of nonlinear ion dynamics in the stabilization of drift-cyclotron and drift-cone instabilities, we have developed a hybrid model (fluid electrons and particle ions) for one-dimensional, fully electrostatic computer simulation. The algorithm suffers no restriction due to electron cyclotron or plasma frequency time scales, and is only required to accurately follow lower hybrid and ion cyclotron frequencies. We shall report on simulation work in progress.

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Twisting Modes

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Abstract

Twisting modes are localized electromagnetic perturbations, closely related to tearing modes; but having odd magnetic field parity, they do not produce magnetic islands. They satisfy a dispersion relation similar to $m = 1$ tearing modes, but twisting modes are not restricted to $m = 1$. We have found unstable modes in three regimes of electron dynamics. In the hydrodynamic electron regime, in which $\omega >> k_{\parallel} v_e$, we find inertial, drift, and collisional modes, all of which require rather weak shear for consistency. In the collision dominated regime, $\nu >> \omega_*$, we find collisional drift modes with $\omega = \omega_* + i\,(k_{\parallel}' \rho\, v_e)^2/\nu$. These modes may occur in the outer layer of present tokamaks, and could be important in large scale reactors. Finally in the adiabatic regime, for which $\omega <<$ $k_{\parallel} v_e$, we find a temperature gradient driven mode requiring $d \ln T_e/ d \ln n > 2$. We have made use of variational [1] and numerical [2] methods in analyzing these modes. Of particular interest is a variational method for dealing with finite k_y and toroidal effects. We find that a single variational principle yields tearing, twisting, and ballooning modes, in appropriate limits.

[1]R.D. Hazeltine, et.al., presented at this meeting.
[2]D.W. Ross, et.al., presented at this meeting.

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The Nonexistence of Absolute Finite Larmor Radius Stabilization*

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A recent paper[1] concerned with finite Larmor radius stabilization of unstable MHD systems proved the following results. First, a system which is MHD stable is also stable in the context of the Vlasov (ion) - Fluid (electron) model. Second, a plasma which is Vlasov-Fluid unstable is also MHD unstable. These proofs assumed monotically decreasing ion distribution functions, (i.e. $\frac{\partial f_0}{\partial \varepsilon} < 0$).

We now show that the converse of this latter theorem is also true. That is, if a system is MHD unstable, then it is also Vlasov-Fluid unstable for monotonically decreasing distribution functions. The reason for this is associated with resonant ion contributions which persist to keep the system unstable until it becomes MHD stable. The immediate implication of this result is that there is no absolute finite Larmor radius stabilization of MHD unstable systems (for the Vlasov-Fluid model). However the growth rates are typically smaller than MHD growth rates by order r_L^2/a^2, when the system is "FLR stabilized."

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Statistical Equilibria of Nonlinear Continuum Mechanics*

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We introduce and derive a formalism for determining the most probable state attained by a system turbulently evolving from an initial state according to any set of coupled nonlinear differential equations that includes incompressible convection of the relevant fields in some phase space. For example, we can treat the two-dimensional electrostatic guiding-center plasma, the two-dimensional inviscid Navier-Stokes fluid, and the Vlasov-Poisson plasma (or its gravitational analog), in which the convected quantities are, respectively, the charge density, the vorticity, and the distribution function.

Suppose $V(\Omega,t)$ is the incompressibly convected field variable in phase space Ω. Then the initial state is prescribed by specification of the total energy and of either a limited number of the moments $\int V^n(\Omega,0)d\Omega$, such as $n=0,1,2$, or the more complete information contained in the specification of the differential volume of phase space occupied by values of $V(\Omega,0)$ between $\bar{V}$ and $\bar{V}+d\bar{V}$ (for all $\bar{V}$). By means of Lagrange multipliers, we incorporate this initial information and the incompressibility constraint into the statistical analysis of a discretized model (in which equal _a priori_ probability assignment can be prescribed unambiguously and in which an entropy function can be defined). We then take the continuum limit and obtain a set of time-independent equations whose solution yields the most probable equilibrium state.

This formalism can be used to determine the most probable equilibrium configuration to be realized under a given set of physical and experimental constraints. We shall present results of the application of this formalism to the above-mentioned physical models. Extension of this analysis to the MHD equations would enhance our understanding of large vortices in liner-confined plasmas and of magnetic field self-reversal in reversed-field pinches.

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Theory of Universal Drift-Wave Eigenmodes in a Sheared Magnetic Field*

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Collisionless universal drift-wave eigenmodes in a sheared magnetic field are analyzed using the WKBJ method. The WKBJ method is motivated here by the larger parameter, L_s/L_n. We find that, in addition to the usual ion-sound turning points, there is a new pair of turning points which are induced by electron dynamics via the Z function. The eigenvalue analysis differs qualitatively depending on whether the shear is strong or weak. In the case with strong shear, $L_s/L_n < (L_s/L_n)_c \sim (m_i/m_e)^{1/4}$, the eigenvalues are determined, for all k_y^2, by the ion sound turning points and the eigenmodes are always damped. In the weak shear case, $L_s/L_n > (L_s/L_n)_c$, the results change qualitatively with k_y^2. For small k_y^2, $k_y^2 < k_{yc}^2$, ion-sound dynamics dominates and, again, the eigenmodes are damped. At k_{yc}^2, the two pairs of turning points (ion-sound and electron-induced) coalesce and the eigenmodes become marginally stable. For large k_y^2, $k_y^2 > k_{yc}^2$, the eigenvalues are now determined by the electron-induced turning points, but the eigenmodes continue to be marginally stable. The basic conclusion then, is that, marginally stable eigenmodes only occur for weak shear $L_s/L_n > (L_s/L_n)_c \sim (m_i/m_e)^{1/4}$ and large k_y^2. In this parameter region, substantial convective amplification of wave-pockets should occur.

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DYNAMICS OF TRAPPED ELECTRON INSTABILITY* DOMINATED TOKAMAK DISCHARGES

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Observations of the data from tokamak experiments show evidence of two different types of discharges. This is most clearly seen in the TFR tokamak. For low values of the plasma current, I_p, the central electron temperature $T_e(o,t)$ rises to a stationary value, whereas for high enough I_p, $T_e(o,t)$ no longer approaches a constant but shows a sharp rise followed by a slow decay.[1] It has been proposed[2] to explain such a behavior by the onset, in the high current case, of the Trapped Electron Mode (T.E.M.) which for the values of the collisionality parameter ν_* usually found in these high current discharges ($\nu_* \approx 0.4$), is likely to produce anomalous transport on both electrons and ions.[3] To confirm this hypothesis, the parameters of a typical TFR discharge[1] have been implemented in the G2M code[4] taking account of anomalous transport in both ions and electrons induced by the T.E.M. We find that this transport is necessary to represent the dynamics correctly:

. for the ions: to fit their observed temperature rise, which is lower by 40% than without T.E.M. transport

. for the electrons: 1) for the temperature to rise at the observed rate, and have the observed spatial profiles, and 2) for the central temperature $T_e(o,t)$ to saturate at the observed level, and then decay.

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Radial Structure of Ballooning Modes*

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The theory of ideal MHD ballooning modes has been advanced beyond Ref. 1. An asymptotic expansion in large toroidal mode number separates the dependence of the eigenfunction in the Hamada coordinates β, V, θ where $\beta \equiv \zeta - q\theta + \int kq' \, dV$ and ζ is ignorable. The stream function for the perturbation is written[2]

$$\phi = \sum_p F(V, \theta - p) \exp[-2\pi i n(\beta + pq)]. \tag{1}$$

Thus ϕ is periodic in θ though F is not. We expand δW to second order in $1/\sqrt{n}$, incorporating multiple length scales in V. By constraining F and k to be slowly varying we make F essentially unique. In lowest order F satisfies the non-periodic Euler-Lagrange equation, $\mathcal{L}(\lambda, V, k) F(\theta) = 0$, where the eigenvalue λ can be determined for each V and k from the boundary condition that F vanish as $\theta \to \pm\infty$.[2,3] In second order we obtain the radial mode structure and

$$\omega^2 = \lambda_o + \frac{1}{4\pi n q'} (\lambda_{VV} \lambda_{kk})^{1/2}, \tag{2}$$

where λ_o is the minimum value of $\lambda(V,k)$, λ_{VV} and λ_{kk} are its second derivatives, and the relation between ω^2 and the true growth rate of the mode depends on the normalization of δW. This can be rewritten in WKB form as

$$2\pi n \oint_{\omega^2 = \lambda} k \, dq = (2N+1)\pi, \tag{3}$$

where the closed contour is along constant λ in the k, V plane. This represents considerable improvement when the mode is less localized either because there are many radial nodes, N, or few toroidal nodes, n. This will be demonstrated by comparison with PEST results.

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Two Dimensional Transport of Tokamak Plasmas*

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A reduced set of two-fluid transport equations is obtained from the conservation equations describing the time evolution of the line density, entropy, and the magnetic fluxes in an axisymmetric toroidal plasma with nested magnetic surfaces. Expanding in the small ratio of perpendicular to parallel mobilities and thermal conductivities yields as solubility constraints one dimensional equations for the surface-averaged thermodynamic variables and magnetic fluxes. Since Ohm's law, $\vec{E} + \vec{v} \times \vec{B} = \vec{R}$, where $\vec{R}$ accounts for any non-ideal effects, only determines the particle flow <u>relative</u> to the diffusing magnetic surfaces, it is necessary to solve a single two dimensional elliptic equation, $\partial/\partial t[\vec{\nabla}\psi/|\nabla\psi|^2 \cdot (\vec{\nabla}p - \vec{j} \times \vec{B} = 0)]$, to find the absolute velocity of a magnetic surface enclosing a fixed toroidal flux. This equation is linear but is nonstandard in that it involves surface averages of the unknown. Specification of $\vec{R}$ and the cross-field ion and electron heat flow provides a closed system of equations. A mixed Eulerian-Lagrangian description is used to calculate the diffusion of plasma quantities through magnetic surfaces of changing shape. As an application, we consider neoclassical transport models for the Pfirsch-Schlüter regime, where $\tau_s/\tau_d \sim q^2\beta$ (τ_s is the skin time and τ_d the diffusion time), and the banana regime, where $\tau_s/\tau_d \sim q^2\varepsilon^{-3/2}\beta$. The predicted discharge behavior for intermediate values of β, $\varepsilon^{3/2}q^{-2}<\beta<q^{-2}$ is analyzed for non-circular cross section plasmas with conducting wall boundaries as well as for free boundary plasmas with external coils.

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Stochasticity, Turbulence, and Anomalous Transport*

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The destruction of magnetic flux surfaces (stochasticity) may have significant detrimental effects on confinement in tokamaks and similar devices. The experimental measurements of anomalous electron heat conduction lend credence to this hypothesis. We review here recent attempts to compute systematically the transport in the stochastic limit, and discuss the relevance of the results for interpretation of the experimental data.

We consider a specified spectrum of radial magnetic perturbations resonant with the rational surfaces of a standard sheared tokamak field. For reasonable spectra one knows a) the approximate perturbation amplitude for stochasticity onset, and b) that most field lines diverge exponentially rapidly in space from one another in the stochastic regime. Workers in many other fields have studied the details of related models in depth. It is thus an amazing fact that no one has given a consistent prescription for constructing the kinetic equation which describes the diffusion of either lines or particles in such a magnetic configuration. We describe here a first approach to this problem by appealing to well-developed techniques of turbulence theory.

The conventional quasilinear theory of the particle distribution is not generally correct for this problem because it misses the important divergence of adjacent lines and consequent rapid particle transport. To construct a proper theory, one must introduce a consistent equation for the joint probability distribution of the particles and field. Such a theory includes the line divergence and predicts from first principles both the scaling and quantitative values of the convergence rate and other characteristic parameters of the stochastic fields. We use these to determine the collisionality regime for several devices of interest, and to find the (test) electron diffusion coefficient in each regime. The relation of these results to those of other groups is discussed.

The theory has an immediate extension to the fully nonlinear problem of turbulence evolving self-consistently with its induced stochasticity. We summarize the related work currently in progress by several groups. Finally, we conclude with a tabulation of outstanding problems.

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ORAL

Theory and Simulations of Trapped-Electron Instabilities*

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Extensive studies have been carried out for the understanding of nonlinear behavior of dissipative trapped electron instabilities and the resultant anomalous plasma diffusion. In the simulation, a 3-D toroidal particle code has been employed with nonuniform density and temperature profiles $\eta_e = d\ln T_e/d\ln N_e \gtrless 0$. Electron-ion pitch angle scatterings with $\nu_e^* \lesssim 1$ are simulated by the Monte-Carlo method. The measured linear growth rate, frequency and mode structure are in reasonable agreement with results from the 2-D eigenmode calculations. The mode is localized around the mode rational surface and shows ballooning phenomena. The nonlinear excitation of convective cells ($\omega \simeq 0$) due to nonlinear coupling of dissipative trapped electron instabilities has been observed along with the anomalous particle diffusion, a phenomena similarly observed in the collisionless drift turbulence. The frequency spectrum and spectral distribution resembles the recent measurements on PLT. The frequency spectrum is very broad and the spectral distribution decreases monotonically with increasing $k_\perp$. With regard to the question of anomalous transport, the electron energy diffusion appears to be larger than the particle diffusion. The observed parallel temperature profile exhibits no appreciable change. However, the electron perpendicular temperature profile undergoes more substantial diffusion. When η_e decreases to $\eta_e = 0$, the instabilities become weaker and the instabilities become stabilized as η_e further decreases to $\eta_e = -1$, in agreement with theoretical predictions.

To understand the generating of convective cells due to drift instabilities and the anomalous particle transport, a mode coupling theory has been developed. The saturation amplitudes of drift waves and convective cells can be estimated to be $(|e\phi^d/T_e|) \simeq (|e\phi^c/T_e|) \simeq (\gamma_k/\omega_k)(\rho_i/L_n)$, and the particle diffusion coefficient due to convective cells is $D_\perp \simeq (cT_e/eB)(\rho_i/L_n)$, consistent with the simulation results. More details on model coupling processes will be presented.

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NONLINEAR EVOLUTION OF TEARING INSTABILITIES: VIOLATIONS OF CONSTANT ψ*

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Tearing modes are believed to play an important role in both the energy confinement and global stability properties of tokamaks. Rutherford[1] showed that the exponential growth of these modes slows to algebraic growth when the magnetic island width w exceeds the linear tearing width Δ. Certain modes which do not satisfy the "constant-ψ" approximation, such as the $m = 1$ tearing mode, however, do not enter the Rutherford regime but continue to evolve exponentially to large amplitude.[2] We present a theoretical model of the nonlinear evolution of such modes which clearly demonstrates the physics behind their continued exponential growth. For these modes the growth rate is comparable to the skin time of the linear tearing layer, and thus when $w > \Delta$, the flux perturbation cannot penetrate the island. As a consequence, the perturbed electric field within the magnetic island approaches zero, and the current there becomes "frozen". Near the x-point, however, the local island width is smaller than the linear tearing width. The mode structure thus remains essentially linear there, and it is the dynamics of the x-point that determine the rate of reconnection and the growth rate of the instability. The essential features of this model have been verified by performing fluid simulations of the nonlinear evolution of the double-tearing and long-wavelength modes in slab geometry using a time-evolutionary, single-fluid, Eulerian code.[3]

The current physical picture suggests that $m > 1$ tearing modes can revert from an algebraic to an exponentially growing phase when their magnetic island width exceeds a threshold. This result may have important implications for understanding the disruptive instability in tokamaks.

*Work supported by DOE and NSF.

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THERMAL MAGNETIC FLUCTUATIONS AND ANOMALOUS DIFFUSION*

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The potential importance of thermal magnetic fluctuations on plasma transport has been recognized recently.[1] In addition to electrostatic convective cells, stationary magnetic fluctuations exist in a thermal plasma which form a set of randomly situated magnetic islands in a shearless system. The important question for the anomalous diffusion due to the magnetic fluctuations (islands) is then the determination of the life time for such magnetic islands. In particular, strong coupling to the electrostatic convective cells are expected since the convective motions of the charged cells can destroy the current filaments causing the damping of the islands.

In order to study the anomalous diffusion and the nonlinear damping, a series of two-dimensional particle simulations have been carried out in three steps. First, ions are treated as a neutralizing background and no electrostatic fluctuations are retained in the simulation. We found the d.c. magnetic islands decay very slowly as predicted by the linear theory. We then turned on the electrostatic fluctuations while keeping the ions as a background. We found that the particle diffusion is orders of magnitude larger than the previous case and the life time of the magnetic islands are much shorter, comparable to the damping of the convective cells. Finally, ion motions are taken into account in the system. In addition to the convective cells and the magnetic islands, lower hybrid waves come into play for the electron diffusion and nonlinear damping of the magnetic islands.

We will compare the simulation results with theory as for the electron diffusion and nonlinear damping for various schemes in k-space such as $k_\perp \rho_e > 1$, $k_\perp \rho_e < 1$ and $k_\perp \rho_i > 1$, and $k_\perp \rho_i < 1$. Effects of magnetic shear tend to reduce the size of the islands but at the same time, plasma currents tend to enhance the magnetic fluctuations. It is possible that the low frequency instabilities can destabilize the magnetic islands. Details will be reported.

*Work supported by USDOE.

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Theory of the Production and Use of RF for Tokamak Plasma Heating in the Electron Cyclotron Frequency Range*

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Programs to develop RF sources in the millimeter wavelength range are presently underway at NRL, Varian and in the Soviet Union. The anticipated availability of these sources will, for the first time, make RF plasma heating practical in the electron cyclotron range of frequencies for large tokamaks.

The following topics are covered:

(1) Review of the theory of the gyrotron and of the current status of source development.

(2) Parameter studies of the feasibility of heating in present-day and reactor tokamaks using the linear theory of wave propagation and absorption.

(3) Evaluation of the possibility of resonant and nonresonant parametric instabilities for such tokamaks.

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Effects of Mutlipole Fields on
the Stability of High Beta Mirrors†

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The stability of a two component guiding center plasma is treated by asymptotic expansions corresponding to the long thin approximation and the approximation of flux surface close to cylinders. These approximations do not give entirely satisfactory treatment of the mirror ends, but they do treat the rest of the system reasonably well. In a previous work an absolute stability condition for axisymmetric mirrors was given and stable profiles were exhibited. In this treatment we include the effect of multipole fields and obtain a local stability condition and explore its implications. We also study spectral properties of the system. We also examine some of the effects of field reversal.

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LBL-7563 ABS

RAY TRAJECTORIES AND EIGENVALUE SPECTRA OF NONSEPARABLE FIELD EQUATIONS*

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For nonuniform plasma with two- (or three-) dimensional variation, one finds an eigenvalue problem $\int dx' \, R(\underline{x},\underline{x}'; \omega)\phi(\underline{x}') = 0$. Geometrical optics[1] leads to ray-trajectory equations $d\underline{x}/dt = \partial\omega/\partial\underline{k}$, $d\underline{k}/dt = -\partial\omega/\partial\underline{x}$, with effective (possibly complex) Hamiltonian $\omega(\underline{k},\underline{x})$, obtained from $\tilde{R}(\underline{k},\underline{x}; \omega) = 0$, where $\tilde{R}$ is the local Fourier transform of R. With suitable boundary conditions, trajectories are confined to toroids[2] in phase space $(\underline{k},\underline{x})$, if a complete set of invariant I_μ exist: $\dot{\underline{x}}\cdot\partial I_\mu/\partial\underline{x} + \dot{\underline{k}}\cdot\partial I_\mu/\partial\underline{k} = 0$. These can be expressed as $2\pi I_\mu = \oint \underline{k}\cdot d\underline{x}$, the integration contours being independent closed curves on a toroid. A canonical transformation generated by $S(\underline{x}; \underline{I})$ produces the new Hamiltonian $\omega(\underline{I})$. Single-valuedness of $\phi(\underline{x})$ then leads to EBK quantization[3] of the invariants $\underline{I}$ as integers (or half-integers) $\underline{N}$, resulting in the eigenvalue spectrum $\omega(\underline{N})$ and eigenfunctions[4] $\phi_{\underline{N}}(\underline{x}) = [\partial^2 S(\underline{x}; \underline{I})/\partial\underline{x}\cdot\partial\underline{I}]^{\frac{1}{2}} \exp iS(\underline{x}; \underline{I})$.

When ray trajectories are stochastic[5] in phase space, EBK quantization fails, and the eigenvalue spectrum $\{\omega\}$ is in some sense random. The eigenvalues are highly sensitive to perturbations.[6]

Applications of these concepts to plasma problems will be presented: drift and lower-hybrid waves in toroids, high-Q toroidal cavity modes, parametric decay instability in nonuniform pump and plasma.

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† Participating Guest; supported by an ONR Research Grant.

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ANOMALOUS INWARD TRANSPORT AND DENSITY RISE IN MAGNETICALLY CONFINED PLASMAS

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It has been observed in Alcator, as well as in other tokamaks, that the plasma density can be increased by injecting neutral gas at the edge of the plasma column. This effect persists even at high densities where the neutrals are necessarily ionized near the edge. Classical plasma transport processes (the Ware effect) are too small[1] to explain the observed rate of increase of line average density ($10^{13}/cm^3$ msec) in Alcator. Recently a model to explain this effect has been proposed.[2] The required inward particle transport results from the excitation of ion drift modes by a relative ion temperature gradient ($\eta_i = d\ln T_i/d\ln n$), coupled with some form of electron dissipation (Landau resonance or finite longitudinal thermal conductivity). We have determined the critical value of η_i necessary to excite these modes in both the collisional ($\omega < \nu_i$) and collisionless ($\omega > \nu_i$) regimes. In the collisional limit the dispersion relation (derived from fluid equations) is a third order polynomial in ω from which stability criteria are easily obtained. In this limit the effects of ion viscosity and transverse thermal conductivity must be included. In the collisionless limit Nyquist's method is employed to determine the stability criterion. The most unstable modes occur for $k_\perp \rho_i \sim 1$. A quasilinear analysis is performed to determine the effect of these fluctuations on particle and thermal transport. The resulting diffusion coefficients and thermal conductivities have been incorporated in a one dimensional radial transport code.[1]

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TEMPERATURE STABILIZATION IN A TOKAMAK REACTOR BY CONTROL OF THE PLASMA POSITION

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Thermally stable operation of a quasi-stationary fusion reactor requires that at the operational temperature the energy losses increase more rapidly with temperature than the fusion power. The possibility of operation in the generally favoured range between 1o and 2o keV then depends critically on the temperature scaling of the energy confinement time which is unknown in that region. Enhanced bremsstrahlung, for example, as dominating loss mechanism would require either operation in the range $T > 4o$ keV /1/ (with consequently unfavourable large values of $\beta \cdot B^2$) or some feedback mechanism for controlling the temperature excursions at a lower, unstable equilibrium value of T. We examine the possibility to use variation of the radial plasma position in a tokamak as a thermal stabilization mechanism, acting through the resulting variations in plasma density and temperature like demonstrated in the ATC experiments. The inherent advantage of this scheme is that the temperature control mechanism acts simultaneously across the whole plasma column, with response times only determined by the power available to the vertical field control system and the time constants of the structural elements acting like an effective copper shell. We give estimates for the radial excursions of the plasma column which have to be allowed for in this scheme and for the power requirements of the control system.

R e f e r e n c e s

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KINETIC THEORY OF ION RING COMPRESSION*

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A general kinetic theory[1] is developed for the adiabatic compression of ion rings in an external mangetic mirror field $B_e(t)$. The single particle distribution function $f(H,P_\theta,t)$ for a collisionless, axisymmetric ring is shown to evolve according to $\partial f/\partial t + U\partial f/\partial H = 0$ in the absence of instabilities and under conditions where the particle motion is ergodic in the poloidal (r,z) plane. Here, H and P_θ are the energy and canonical momentum of a ring ion, and U is a spatial average of the toroidal betatron electric field over the region of the r,z plane which is accesible to an ion with constants H and P_θ at time t. A complete description of ring compression is obtained from the equation for f, which gives the ring current-density $J_{b\theta}$, from an appropriate constitutive relation for the plasma response, which gives the plasma current-density $J_{p\theta}$, and from Ampère's law. The description is simplified by the existence of an adiabatic invariant, $I(H,P_\theta,t)$, of the ring particle motion. This allows an explicit solution for f during compression as $f = F(I,P_\theta)$, where F is an invariant function. The theory is valid for rings of arbitrary aspect ratio having large and/or small gyroradii orbits, and it allows for ring particle evaporation. The theory has been applied by Larrabee et al.[2], for compression ratios of up to 10^2. A general analysis is made of energy and angular momentum conservation during compression. In particular, the total power input and the power absorbed are derived in terms of the magnetic moment of the ring-plasma system, $M(B_e)$.

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ON THE STABILITY OF BOUND EIGENMODE SOLUTIONS FOR THE COLLISIONLESS UNIVERSAL INSTABILITY

T. Antonsen, Jr.

The collisionless universal instability in slab geometry with a sheared magnetic field is considered. It is shown from the differential eigenvalue equation that no bound growing eigensolutions exist. The method of solution consists of first assuming that exponentially growing eigenmodes exist and then forming quadratic quantities from which a contradiction is obtained. The relation between the eigenmodes and convective modes is discussed.

KINETIC THEORY OF BALLOONING INSTABILITIES*

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We have developed a kinetic formulation for large toroidal mode number, electrostatic and electromagnetic ballooning instabilities in a weakly collisional plasma in a sheared magnetic field and arbitrary axisymmetric geometry. Our theory includes full electron parallel motion and ion gyroradius effects and considers the global structure of ballooning modes, nonlocal in both the radial and poloidal directions. For the latter purpose we have derived a novel representation for the modes which correctly describes both their azimuthal periodicity and their long parallel wavelength. We find that a single parameter, independent of beta, controls the transition from electrostatic to electromagnetic ballooning. The behavior of the electromagnetic modes is dominated by the plasma self-inductance. Electrostatic ballooning occurs for large resistivity and large azimuthal mode number, even in high-beta plasmas. In a rather collisional plasma, neglecting diamagnetic and Larmor radius effects, we recover the classical growth rate for resistive ballooning when shear is absent, but find shear to be stabilizing when $rq'/q \geq O(1)$ where q is the safety factor and r the minor radius. In a semi-collisional plasma where electron diffusion along field lines becomes important, the resistive ballooning is stabilized by kinetic effects when $k_\perp \rho_s > 1$ where ρ_s is the Larmor radius of ions at the electron temperature. Resistive ballooning appears to be more significant than the electromagnetic type, however, because the former has no beta limit. The resistive ballooning instability can have a large-scale, convective cell-like structure and, therefore, may explain the anomalous energy loss observed in tokamaks.

*Work supported by NSF and USDOE

ENHANCED TRANSPORT IN LOW FREQUENCY HEATING OF MAGNETICALLY CONFINED PLASMAS BY ISLAND FORMATION*

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Recent experiments have been performed attempting to heat plasmas confined in toroidal magnetic systems by means of rf at low frequencies, typically, well below the ion cyclotron frequency.[1,2] The basic motivation for these experiments came from theoretical work predicting absorption of Alfvén waves in inhomogeneous plasmas.[3,4] While significant heating has been observed in all of these experiments, they have also been characterized by significant loss of plasma during the heating. In the Proto-Cleo stellarator at Wisconsin, such loss was found to be linearly proportional to the amplitude of the modulating field.[5]

The launch coil for the Alfvén waves in Proto-Cleo was an m=3, n=1 winding, compared to an m=3, n=7 confining field winding. Since the multiplicities of the windings differ, it is quite likely that magnetic islands would form at appropriate resonant regions. In addition, if the heating frequency is low, as is the case for Alfvén waves, perturbations of the magnetic field can penetrate into the body of the plasma.

In order to test this assumption, the vacuum magnetic surfaces for Proto-Cleo were calculated numerically, by following magnetic field lines around the torus, including the effects of the rf launch coil. With approximately 1.5% modulation, a typical experimental value, magnetic islands are noticeable. Also, since a vertical field is also generated by the launch coil, the magnetic axis also moves. Since the island width is proportional to the square root of the modulating field amplitude,[6,7] then, assuming that the step size for diffusion is now the island width, the confinement time is decreased by an effective diffusion coefficient whose amplitude is directly proportional to the field amplitude, as is the case in this experiment.

Hence, enhanced transport by magnetic island formation is a real occurrence in low frequency rf heating of magnetically confined plasmas.

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INVESTIGATION OF TRAPPED-PARTICLE INSTABILITIES IN EBT*

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An investigation is presented of the role which trapped particles might play in the drift wave stability of EBT. The model adopted consists of a bounce-averaged drift kinetic equation with a Krook collision operator. Care has been taken to model, at least in an elementary way, the features which distinguish the physics of EBT from that of tokamaks, namely the large magnitude and velocity space dependence of the poloidal drift frequency Ω, the relatively small collisionality ν/Ω, the enhancement of ν_{eff} for passing particles and the closed nature of the field lines. Instabilities are found which have a somewhat dissipative character, however the precessional drift is found to be a significant stabilizing influence. In most cases the modes are completely stabilized when $\omega_*/\ell\Omega \lesssim 1$ for normal gradients. For reversed gradients ($\omega_*/\ell\Omega < 0$), stability is greatly enhanced.

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DRIFT-ALFVÉN WAVES IN TOKAMAKS*

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The recent development of microscopic magnetic island theories to explain the anomalous electron heat transport in tokamaks has stimulated a renewed interest in the investigation of radial eigenmodes of finite beta (ratio of the plasma pressure to magnetic pressure) drift waves in a sheared magnetic field. The coupled second order differential equations for $\tilde{\phi}$ and $\tilde{A}_\parallel$ that are employed to study finite β drift waves permit both unstable drift waves and unstable shear Alfvén waves in the local approximation in which the shear is neglected. Previous analytic calculations retaining magnetic shear resulted only in finite β modifications of the fundamental drift wave. A shear Alfvén wave has not to our knowledge been recovered in a tokamak geometry.

We report here a numerical solution of the radial eigenmode equations which reveals the existence of a new branch in addition to the branch that evolves gradually from the electrostatic drift wave. This new branch is heavily damped in the low β regime and has no electrostatic limit counterpart. The real part of ω for this branch is very close to ω_{*e} so that the perturbed current is significant only at or outside the electrostatic turning point x_t where the ion sound term becomes significant. The mode is most unstable when the Alfvén distance x_A, the distance from the rational surface where the frequency is equal to the local shear Alfvén frequency, falls within the region of significant perturbed current. This occurs when $x_A > x_t$. We thus identify this mode as a shear Alfvén wave. Numerical results show that both the drift and shear Alfvén branches are always stable in a collisionless plasma for β up to 10%. This is not predicted by previous analytic calculations. When trapped electrons are included, the electrostatic drift mode becomes unstable. However, finite β has a stabilizing effect on it. The shear Alfvén branch can also be destabilized by trapped electrons and becomes more unstable as β increases.

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MACROSCOPIC STABILITY OF THE SPHEROMAK

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ABSTRACT

We consider the limiting case of low-aspect-ratio, D-shaped tokamaks. To avoid singularity of the coil stresses, the toroidal-field coils must be eliminated; the toroidal field then vanishes outside the plasma.

The plasma is bounded by a shell or a vacuum region; by modifying the boundary condition alternative shapes may be found, such as prolate and oblate spheromaks.

A low β oblate spheromak, with a conducting shell at about $1.3-1.5\, r_0$ (where r_0 is the characteristic dimension), will be stable against all macroscopic modes. A low β prolate spheromak is unstable only against tipping of the magnetic axis. Critical β are currently being computed however as the spheromaks are unstable against localized modes.

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Nonlinear MHD Modes and Bifurcation†

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This is a review of our work on the nonlinear behavior of m=1 and m=2 linearly unstable MHD modes.

The basic framework is developed in the m=1 study (Pao, Phys. Fluids, May, 1978), leading to the nonlinear equation $\ddot{A} = \lambda^2 A + \alpha A^3$ for the mode amplitude A(t). When the mode is nonlinearly stabilized, the plasma does not go to a final equilibrium but undergoes non-sinusoidal periodic motion. The meaning of the conventional bifurcation analysis is clarified. In particular, the theory shows that the bifurcated equilibria calculated in the bifurcation analysis are not the final state but are actually the two centers of the phase diagram of the nonlinear equation which are not connected to the unperturbed equilibrium by dynamic motion and the linear stability analysis of the bifurcated equilibria is redundant. Flux conditions are also examined.

The theory has also been applied to the Shafranov m=2 mode (Pao and Rosenau, CPAM, Dec. 1978) and the results show this mode is always nonlinearly stabilized, contrary to previous bifurcation results.

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Macroscopic Transport Model for a Reversed Field Mirror Machine†

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Consider the buildup of a mirror confined plasma including the possibility of field reversal. A strong theoretical indication has been given (ideal model, without transport) that field reversal will occur naturally without injection, if the coils are properly programmed.[1] To be more realistic, we use a model with resistivity and heat flow using the Grad-Hogan longtime scale transport formulation. The plasma velocity (mass flow) is eliminated just as in the adiabatic theory to obtain 1-D transport relations with geometrical coefficients updated at intervals by a 2-D equilibrium solution. There are three dependent variables (equivalent to p, T, ψ) which satisfy two transport equations and one ODE. There is a 2×2 matrix of transport coefficients (and time constants); in simple limiting cases they reduce to classical mass transport and heat flow (there is no skin effect or time scale associated with it in this problem). The time constants are $\tau = \frac{1}{2}(\tau_o+\tau_1) \pm \frac{1}{2}[\tau_o^2+\tau_1^2 - 2\beta\tau_o\tau_1]^{1/2}$ where τ_o and τ_1 are the classical diffusion and heat flow times respectively $[\beta = p/(p + \frac{1}{2}\langle B^2\rangle)]$. By analogy with a successful model for Doublet formation[2], the reversed field island formation rate should not be restricted to the time scale of any transport mechanism.

The vacuum-plasma interface is quite singular with all quantities approaching zero or infinity at fractional powers of the distance. The separatrix is also singular with logarithmic dependence of some quantities. Another analytic singularity occurs at the center of an island because the "large" Hall factor $\omega^2\tau^2$ is zero.

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Poloidal Asymmetry of Impurity Ion Distribution in Tokamaks*

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The poloidal asymmetry in the distribution of a trace amount of impurity ions in tokamaks is computed in the Pfirsch-Schlüter regime. Accounts are taken of the poloidal electrostatic field as well as the parallel particle and heat flows that exist in a pure plasma in equilibrium. The same parametric dependencies as are observed in Alcator are predicted, although detailed quantitative predictions are subject to large error due to the uncertainty in the plasma profiles.

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INTERACTION OF CURRENT FILAMENTS IN A MAGNETIC FIELD*

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It has been shown[1] that for a plasma in thermal equilibrium the magnetic interaction of currents which are generated by particles moving along magnetic field lines gives rise to a zero frequency collective motion similar to that of the electrostatic convective cell of two-dimensional guiding center plasma theory. Motivated by this discovery and the existence of negative temperature states in 2D guiding center plasmas and line vortices systems, we have derived a nonlinear differential equation which governs the steady-state current distribution for a two dimensional line current model. This equation allows analytical solutions of multipole current distributions (magnetic islands) which correspond to negative temperature states. This model may be helpful in understanding the confinement magnetic field structures. Results will be presented and discussed.

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*Work supported by Department of Energy, Contract EY-76-C-03-0167, Project Agreement No. 38.

ENERGY CLAMPING OF RUNAWAY ELECTRONS*

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An idealized problem is investigated which illustrates the role of wave particle interactions in the evolution of runaway beams. The model considers the interaction between a weak cold beam, driven by an external static electric field, and waves quantized by the geometry. The waves may correspond to Gould-Trivelpiece modes fixed by the length of a small toroidal device, or to the finite Fourier modes encountered in computer simulations. The physics consists of the sweeping of the accelerated beam through the resonance provided by each cavity mode. This process is formulated in analogy with the O'Neil, Winfrey, Malmberg (OWM) problem[1] but uses a spatially averaged description based on the exact energy and momentum conservation laws with the dynamics simplified through a WKB representation of the dispersion relation. This model shows that the energy of the beam can be clamped with the momentum push being transferred to the waves, thus resembling the clamping behavior observed recently[2] in the Microtor tokamak.

*Work supported by ONR and DOE.

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Threshold Saturation of the Drift Cyclotron
Loss Cone Instability

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We consider an empty loss cone distribution near the critical density gradient $\varepsilon = (1 + \Delta)\varepsilon_c$. The nonlinear saturation amplitude of the time asymptotic potential fluctuation is determined for the single mode which goes unstable. In this first evaluation, the linear mode has no z-variation and radial calculations are in the local approximation. For delta-like perpendicular velocity distributions the plasma density is chosen to satisfy $\omega_{pi} < 4.12\ \Omega_i$ in order to suppress the Harris instability[2] (for which $\varepsilon_c = 0$). The modified particle distribution functions and nonlinear potential are obtained for these equilibria. Saturation is due to nonlinear broadening of the velocity distribution. The nonlinear frequency shift plays no role and in fact is indeterminate. This is quite different from the behavior predicted by Aamodt et al. for saturation of the large amplitude drift cyclotron mode[2]. The effect of the nonlinear electric field which develops is also small. An analytic saturation condition predicts a stable amplitude as a function of Δ. Further details of the saturation mechanism will be discussed. Extension of the results to more general perturbations and equilibria, including the effects of finite ion temperature will also be discussed.

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ALPHA PARTICLE COLLISIONAL TRANSPORT IN THERMONUCLEAR PLASMA*

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The time evolution of the density, momentum, kinetic energy and heat flux of the alpha particles in calculated by taking moments of the Fokker-Planck equation. The electron and background ion contributions are calculated separately to show the effect of each species. Using the analytic expression for the alpha particle distribution obtained previously by the authors by solving the Fokker-Planck equation, estimates are obtained for the momentum transfer, energy exchange and heat flux. The effect of a weak parallel electric field is included as a perturbation.

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NUMERICAL COMPUTATION OF PLASMA BEHAVIOR IN RELATIVISTIC ELECTRON BEAM TARGETS

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ABSTRACT

Recent experiments have been reported [1] in which 1.5 mm diameter plastic shells containing deuterium-tritium fuel were irradiated and imploded by a single beam from the REHYD REB accelerator (1 MeV, 250 kA, 100 ns). The target design permitted a portion of the beam current to enter the target to provide fuel preheat and magnetic thermoinsulation. Initial results indicated that $\sim 10^6$ neutrons were produced in the experiments.

Using the computer code ANIMAL, a fully time dependent, non-linear, two-dimensional magnetohydrodynamic code, we are computing the fuel behavior in the target during both the preheat and implosion phases. Our calculations take into account ionization, resistive diffusion, thermal conduction with full $\omega\tau$ dependence, radiation, magnetic fields due to both plasma and beam currents, and the spherical geometry of the targets. The alternating-direction implicit numerical methods used in ANIMAL allow an acceptable time step to be used in the computations even though CFL restrictions near the origin in the spherical coordinate system used would be prohibitive.

Our calculations show that during the 1 microsecond preheat phase, the fuel becomes significantly magnetized and is elevated to a mass average temperature of 5 eV with a low density 22 eV central region. During the implosion, some fuel reaches a temperature of 400 eV. With a radius convergence of 20, 10^6 neutrons are produced, in reasonable agreement with experimental measurements, suggesting that the origin of the experimental neutrons is thermonuclear.

Our computations are displayed in computer generated movies. The movies suggest that only Eulerian numerical methods can adequately handle the dynamic plasma motion.

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SOURCE EFFECTS UPON COLLISIONAL TRANSPORT IN TOKAMAKS

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In the collisional regime, flows are set up in the flux surfaces to prevent the charge separation induced by curvature and ∇B drifts. Poloidal flows result in a parallel collisional momentum transfer between different plasma species which drives the radial particle and heat fluxes.[1] When a poloidally asymmetric particle and/or energy source (sink) is present, these poloidal flows are modified, resulting in modified radial fluxes.[2,3] Introduction of a particle or energy source will in general also result in the introduction of a momentum source (sink). The parallel momentum transfer between the source and the plasma ions drives radial particle fluxes in the same manner as does the collisional parallel momentum transfer between different plasma species.

The theory for the radial particle and heat fluxes in the presence of particle, momentum and energy sources has been worked out for a collisional, axisymmetric toroidal plasma in the large aspect ratio limit.[4] Expressions have been developed for estimating the relative magnitude and the sign of the parallel momentum transfer effect and of the poloidal asymmetry effect, as a function of source injection geometry and the plasma parameters. This theory has been applied to estimate the magnitudes of these two "source effects" in the ISX-A flow reversal experiment.[5]

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ON THE TRANSPORT OF IONS WITH MULTIPLE CHARGE STATES IN NEOCLASSICAL THEORY*

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In tokamak plasma transport calculations, it is sometimes necessary to account for the transport of the different charge states of impurity atoms separately, without invoking the coronal approximation. Neoclassical transport coefficients are now available for multispecies plasmas in a variety of collisionality regimes, but the computation of these coefficients involves the inversion of large matrices. Since, in addition, the time evolution equations for the densities of all species are coupled, the running time for one-dimensional diffusion calculations increases rapidly with the total number of species and charge states. We find, however, that neoclassical transport coefficients simplify substantially in the "disparate clump" approximation. In this approximation the plasma may contain many charge states of each atomic species, so long as the different atomic species are disparate in mass. Using this approximation, we have calculated, in analytic form, the Spitzer function for a multispecies plasma. Further, with the aid of general relations which have been developed recently,(1) we derive from this Spitzer function tractable expressions for the Ware flux and bootstrap current transport coefficients. In the Pfirsch-Schlüter regime, we have obtained simple, analytic results for the transport coefficients. It is found that, for a collisionally dominated plasma, the particle and energy diffusion equations can be transformed so that the matrix of diffusion coefficients becomes very sparse. As a result, a particularly efficient method has been developed for solving these diffusion equations.

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EFFECT OF TEM ON OXYGEN IN TOKAMAKS*

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The trapped electron mode (TEM) is expected to produce anomalous transport of tokamak impurities in the same way as it has been previously shown to affect the transport of electrons and ions.[1] The particle flux which results from this effect has been calculated[2] and takes the form:

$$\Gamma_j^{(TM)} = -\frac{C}{Z_j}\frac{\partial n_j}{\partial r}$$

where $C(r)$ is a coefficient depending on ne, T_i, and T_e. Such anomalous terms are of interest, as experiment shows a discrepancy with the predictions of neoclassical theory.[3,4] A simple model including the TEM effect has been formulated and implemented in a numerical model of oxygen dynamics, which calculates steady-state density profiles with Hinnov[5] atomic rates and Pfirsch-Schluter transport,[6] and again with the addition of the TEM terms. The agreement with TFR data[7] is considerably better in the latter case, especially with respect to the profile of Z_{eff}, which becomes flat when the new terms are added.

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ORBITAL RESONANCES IN QUADRUPOLE-STABILIZED MIRROR CONFIGURATIONS*

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ABSTRACT

Using analytic techniques and the particle-orbit code ORBXYZ, we demonstrate that a quadrupole field added to an axisymmetric nonvacuum mirror configuration significantly couples the radial, azimuthal and axial motions of single particles, and that this effect may account for the bursting and non-bursting anomalous losses observed in the RECE-Berta experiment.[1] At particular values of the plasma self-field, a class of resonant particles can experience sizeable excursions from an initial set of radial and axial oscillation amplitudes. If the plasma radius is defined by a limiter, as in RECE-Berta, then resonant particles hitting the limiter would give rise to a sudden loss of plasma. We obtain analytic estimates for the resonance conditions and resonance widths, and from these estimate the size of a burst. Orbit code calculations in steady-state and time-varying fields are used to show the effect. A movie of results from a time-varying field will be presented. We show that, between bursts, resonances mainly affect particles away from the limiter, giving rise to an enhancement of classical diffusion, such as is also observed in RECE-Berta. In 2XIIB, resonance effects should be considerably smaller at a given fraction of field reversal, and should not be manifested as bursts.

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SPATIAL EIGENMODES FOR THE ALFVEN-ION-CYCLOTRON INSTABILITY IN FINITE-LENGTH PLASMA*

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ABSTRACT

We are motivated to find the improvement in AIC stability brought about by finite axial length. We also wish to understand the eigenmode structure. For ease of investigation, we choose a finite plasma model where ions are confined by a parabolic electrostatic potential well and lie in a uniform magnetic field. The electrons maintain quasi-neutrality. The Maxwell-Vlasov system is solved in full including the ion bounce motion.

Firstly, we derive heuristic dispersion relations; secondly, we calculate exact stability limits; thirdly, we display the important eigenmodes. Modes with spatially-even E-Fields are shown to have resonances at $\omega = \omega_{ci} \pm 2n\omega_{bi}$, while modes with spatially-odd E-fields have resonances at $\omega = \omega_{ci} \pm (2n-1)\,\omega_{bi}$. Here ω_{ci} and ω_{bi} are the ion cyclotron and bounce frequencies.

The lowest order odd mode is the most unstable. The onset of instability roughly agrees with that deduced from the infinite-medium dispersion relation and the requirement that a half-wavelength should fit in the plasma. These results are in accord with those from Byers' linearized particle simulation code, which uses the same finite-plasma model. Byers' code has a linear-polarization constraint which introduces additional resonances with $\omega_{ci} \to -\omega_{ci}$ in the equations above. This leads to the complication of double resonances when $\omega_{bi} = \omega_{ci}/n$.

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TIME-DEPENDENT TANDEM MIRROR CONFINEMENT STUDIES*

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ABSTRACT

The tandem mirror rate code TAMRAC integrates rate equations for number and energy of an arbitrary number of species in a tandem mirror machine. In addition to sources and endloss[1,2], the code includes a model for enhancement of plug loss due to the drift-cyclotron loss cone mode (DCLC), externally supplied stream to stabilize DCLC, supplemental electron heating, a model for species-dependent radial diffusion, and provision for injecting hot (not electrostatically confined) ions in the solenoid. Results from two studies will be presented: (1) a study of startup in the Tandem Mirror Experiment (TMX) which indicates that near steady-state conditions can be achieved on a time scale allowed by the power supplies if the gas feed is suitably programmed, and (2) a study of alpha particle buildup in a tandem mirror reactor, and ways of preventing buildup to a level that seriously degrade reactor Q. One particular means of eliminating hot alpha particles, nonadiabatic scattering (magnetic moment stochasticity), is discussed in more detail.

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G. Conn, Michigan State University, Department of Mathematics, East Lansing, MI 48824 and J.A. Tataronis, New York University, Courant Institute of Mathematical Sciences, New York, NY 10012.
Perturbation of the Alfvén Continuum by the Hall Effect.

The objective of this analysis is to determine the influence of the Hall effect on the Alfvén wave continuum. It can be shown in several cases of practical interest, such as Alfvén wave heating of Tokomaks, that the dominant term in a generalized Ohm's law is the Hall effect when the frequency is of the order of the ion cyclotron frequency. We take as our model Ohm's law in the form $\underset{\sim}{E} + \underset{\sim}{v} \times \underset{\sim}{B} = \epsilon/\rho \, \underset{\sim}{J} \times \underset{\sim}{B}$, where ϵ is the mass to charge ratio for ions, and the linearized equations of MHD. The Hall effect introduces the ion cyclotron frequency to the problem and allows analysis of higher frequencies than those contained in ideal MHD. As a special case we consider a θ-pinch surrounded by a vacuum region and assume that linearized quantitaties depend on θ, z and t in the form $\exp i(\omega t - m\theta - kz)$. We obtain a fourth order system of ordinary differential equations for u and p_*, the linearized radial velocity and total pressure. The system has a turning point at the Alfvén singularities of ideal MHD. This fourth order system replaces the second order system of ideal MHD. We must specify two further boundary conditions. First the component of the magnetic field normal to the plasma-vacuum interface must vanish on both sides of the interface. There is one further condition on the magnetic field at $r = 0$. We analyze the system for small ϵ by the method of matched asymptotic expansions. For the case $m = 0$ and $\nabla \cdot \underset{\sim}{v} = 0$ the solution near the turning point is given explicitly in terms of Fresnel integrals and a related function. We show that the Alfvén continuum of ideal MHD is replaced by a discrete set of eigenvalues with a spacing of order ϵ. We consider passage to the limit of ideal MHD for an initial value problem by letting $\epsilon \longrightarrow 0$ and discuss the significance of these results for Alfvén wave heating.

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Streaming Instabilities in a Plasma
With Electron or Ion Rings*

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We investigate in this paper the high frequency two stream instability in a plasma situated in a magnetic field that simulates a field-reversed geometry. A plasma model is used in which one of the components is a beam which is taken to be monoenergetic but with an angular spread in the direction of propagation. The second component is taken to be a background magnetoactive cold plasma. A perturbation analysis is carried out to derive the dispersion equation from which the growth rates for the extraordinary and electrostatic modes are calculated for magnetic field strengths in the range for which $\Omega_e/\omega_p = 1/2 \rightarrow 2$.

A detailed examination of the dependence of the maximum growth rate on the angle of beam propagation relative to the magnetic field, as well as the contribution of Landau damping is also carried out. The functional form of maximal growth rates for the angular spread and energy of the beam will be presented where it will be shown that these parameters have a stabilizing effect. Application of these results to the RECE experiment with its relativistic electron ring, as well as devices with ion rings such as the Ion Ring Compressor[1] reactor model will be discussed.

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THEORETICAL INTERPRETATION OF NONLINEAR RF COUPLING IN RECENT GENERAL ATOMIC LOWER HYBRID HEATING EXPERIMENTS*

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ABSTRACT

A physical model that takes into account ponderomotive effects at the edge of the plasma is capable of predicting a saturation in RF coupling at high power levels. The model equation describing the coupling is solved numerically for realistic profiles. The results are in agreement with analytical solutions of simple models such as the one-step and two-step models. The transmitted power as a function of the applied field energy is evaluated over a wide parameter regime. For low power levels, the transmitted power is linearly proportional to the applied energy. Saturation occurs when the applied field is sufficiently strong to modify the edge profile. This nonlinear coupling effect is more pronounced for shorter wavelengths. At the power level of present tokamak lower hybrid heating experiments, some edge profile modification is likely to occur. The results are used to interpret recent observations in the GA Octopole lower hybrid heating experiments.

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COMPARISON OF GLOBAL AND LOCAL STABILITY ANALYSES OF THE BALLOONING MODE*

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ABSTRACT

The betas for D-shaped tokamak equilibria which are marginally stable to the ballooning mode, are numerically calculated from the global analysis with ERATO[1] and the local analysis with BLOON[2,3]. We find that the BLOON results for β_c are slightly more pessimistic than those of ERATO. Agreement between ERATO and BLOON improves when "radial" structure corrections[4] are added to the local ballooning mode analysis. The values of $\beta_c(q_o)$, where q_o is the safety factor on axis, lie along the same "universal" curve, whether or not the radial structure is taken into account. Thus, the maximum possible β_c for a given peaked current profile is independent of the radial structure.

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Efficient High Power Gyrotron Travelling Wave Amplifier - Theory and Simulation*

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The gyrotron (electron cyclotron maser) is a new source of powerful microwave radiation at the millimeter and submillimeter wavelengths. In connection with controlled fusion research, the gyrotron has already shown great promise for electron cyclotron resonance heating of tokamaks. In the amplifier configuration, it consists of an annular electron beam propagating along helical trajectories under the guidance of an axial magnetic field inside a fast wave structure such as a waveguide. For ECRH applications, efficiency optimization of such a device is of primary importance. We have studied this problem both analytically and with numerical simulations. An idealized electron beam of the type formed by a magnetron injection gun was assumed and investigated using the relativistic Vlasov and Maxwell equations. A detailed linear dispersion relation was derived, on the basis of which analytical scaling relations for the growth rate and efficiency have been obtained. The linear gain and bandwidth were also calculated. A single wave simulation code was used to study the saturation mechanisms of higher cyclotron harmonic interaction and to calculate the beam-to-wave energy conversion efficiency. The results are in good agreement with analytical predictions. Methods of parameter optimization for maximizing the efficiency were considered in detail. The parameter optimization involves the determination of the point of maximum device efficiency as a function of beam density, beam energy, beam positioning, and external magnetic field for the output power required. The optimized parameters can yield specific design data for gyrotron travelling wave amplifiers with efficiency of ~ 50% and power in excess of 300 kW.

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MAGNETOHYDRODYNAMIC SIMULATION OF PLASMA FORMATION IN TORMAC*

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Previous methods used at Columbia for simulating imploding pinches are revised to study the formation of the plasma in TORMAC. The plasma is initially at rest, and carries a toroidal bias field and a small toroidal current, which gives closed field lines. The main cusp fields and main toroidal field are then applied as given functions of time. Single fluid magnetohydrodynamic equations are solved, for the purpose of obtaining the plasma shape at the end of the compression.

The exact formulation of the problem is presented. Since TORMAC does not have an outer conducting shell, the vacuum field equations must be solved in an infinite domain. Two different methods are used to treat this. In the first method, we use a virtual conducting shell, on which fictitious surface currents flow. The effects of these currents are rigorous subtracted off using Green's functions. In the second method, the infinite domain is first mapped into a finite domain, over which the vacuum equations are then solved. This method is faster and more accurate than the first one. These two methods are compared in detail for a model problem, in which the plasma is replaced by a solid conductor, and the diffusion of the bi-cusp field is solved as an initial-boundary value problem.

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Nonlinear Electric Field-Driven Transport in Tokamaks

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Abstract

The particle flux, electron heat flux, and parallel current density have been calculated to third order in $E_\parallel/E_c$, the ratio of parallel electric field to the critical field for electron runaway. Assuming that Z_{eff} falls in the range $1 << Z_{eff} << (E_c/E_\parallel)^2$, the banana regime fluxes have the form

$$\Gamma_e = \epsilon^{\frac{1}{2}} n_e \left(\frac{c\,E_\parallel}{B_p} \right) \left[-\tfrac{3}{2} + C_1 \left(\frac{E_\parallel}{E_c} \right)^2 \right]$$

$$q_e = C_2\, \epsilon^{\frac{1}{2}}\, n_e T_e \left(\frac{c\,E_\parallel}{B_p} \right) \cdot \left(\frac{E_\parallel}{E_c} \right)^2$$

$$j_\parallel = \frac{32}{3\pi} \frac{n_e e^2 \tau_e}{m_e} E_\parallel \left[1 - \tfrac{3}{2}\, \epsilon^{\frac{1}{2}} + C_3 \left(\frac{E_\parallel}{E_c} \right)^2 \left(1 - C_4\, \epsilon^{\frac{1}{2}} \right) \right]$$

The numerical coefficients C_1, C_2, and C_3 are large enough that these nonlinear fluxes may be experimentally significant, for $E_\parallel/E_c > 0.1$.

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Variational Methods for Electromagnetic Instabilties

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Abstract

Recent advances in the theory of electromagnetic eigenmodes in tokamak plasmas - including drift-tearing modes, twisting modes and drift waves - have depended upon variational solution of the radial eigenmode equations. Variational principles in configuration space (x) are usually unwieldy unless either (i) the perpendicular wavelength is much larger than the radial mode width, $k_\perp << \partial/\partial x$, or (ii) the plasma conductivity $\sigma(x)$ is effectively constant. For case (i), a variational principle described previously[1] can treat arbitrary variation of $\sigma(x)$, including electron resonance and adiabatic effects, without difficulty. It yields, in particular, a unified dispersion relation describing accurately both $m = 1$ and $m \geq 2$ tearing modes. For case (ii), a generalization to $k_\perp \neq 0$ of Wong's variational principle[2] can be used. The equivalence between this generalization and the variational principle of Berk and Dominguez[3] is demonstrated. But finite - $k_\perp$ effects are most easily treated by means of a new variational principle in wave-vector space (k_x), which also applies to ballooning instabilities. The k_x-space variational principle is used here to study previously neglected finite-$k_\perp$ effects on both $m = 1$ and $m \geq 2$ tearing modes.

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TOROIDAL FUSION ENERGY AMPLIFIER VS. IGNITION REACTOR

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The requirement for ignition operation of a D-T fusion reactor is well known. Point model predicts thermally stable operation at 25 keV for $n\tau_E = 1.5 \times 10^{14}/f\ cm^{-3}$-sec, where f is the fraction of fusion alpha energy deposited in the plasma. If the reactor is designed to operate in the driven mode as an energy amplifier, significant net energy output can be realized over a wide range of more relaxed operating parameters. In general, pre-burning of the injected fuel in the two component mode assures electrical breakeven and the system can then be driven as intensely as necessary to maintain thermonuclear fusion for net energy output. Net power condition can be demonstrated at $n\tau_E = 10^{13}\ cm^{-3}$-sec with reasonable beam current. The relaxation in $n\tau_E$ implies smaller reactors and higher tolerance for impurities. The flexibility in operating temperature permits optimization for power density and control of power level. In regimes of economic interest, the beam power required to drive the system is comparable with supplementary heating power required for ignition reactors. In comparison, therefore, driven system offers advantages over ignition reactor in scientific, technological and economic considerations for both developmental prototypes and certain commercial power installations.

SHEAR DAMPING OF DRIFT MODES IN THE PRESENCE OF A STRONG SHEAR AND A PERIODIC GRAVITY

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In order to study the effect of a spatial modulation of the plasma equilibrium along the lines of force of a strongly sheared magnetic field $\vec{B}$, we consider a slab model with density gradient dn/dx and a gravity force g_x which varies periodically in the y - direction, assuming $|B_y(x)| \ll B_z$. The modulation couples the drift modes, centered on neighboring rational surfaces, giving rise to a ballooning effect. We study the differential equation for the Fourier components of the perturbed electric potential, first neglecting the modulation of the shear term.

Expanding in powers of ε (the ratio of g-drift to grad n-drift velocity, $\varepsilon \sim r/R$) we obtain a series expansion of the shear damping γ_s which converges for not too large ε.

For larger ε, a solution is obtained by simplifying the equation in different domains of the variable and joining the solutions. The γ_s thus obtained is a decreasing function of ε, depending on the shear Θ and the distance between uncoupled modes Δx, through $\Lambda \sim \Theta (\Delta x)^2$. This effect is enhanced when the modulation of the shear term is included. We have calculated numerically the curves of constant γ_s in the plane (ε, Λ). It is found that the reduction of γ_s depends strongly on the perpendicular wave number k_y. For certain types of drift waves, this dependence may appreciably change the spectrum of unstable wave numbers.

Influence of D-Shaped Plasma Cross Sections on m=1 and m=2 Modes*

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The MHD stability properties of a straight helical $\ell = 1,2,3$ high-β stellarator configuration with respect to m=1, k=0 and m=2, k=0 perturbations have been investigated using a computer code |1| which takes into account a vacuum region between the plasma and the outer conducting wall. The $\ell=1$ equilibrium configuration has a zero rotational transform, a short periodicity length, and a large $\ell=1$ distortion of the outer conducting wall. The superimposed helical symmetric $\ell=2$ and $\ell=3$ distortions of the wall can also have large amplitudes. We have investigated the dependence of the rate of change λ of the m=1, k=0 mode on the $\ell=2$ and $\ell=3$ distortions. We found that an $\ell=2$ field does not reduce the growth rate of the unstable m=1 mode. An $\ell=2$ field together with an $\ell=3$ field or the $\ell=3$ field alone reduces the growth rate or even stabilizes this mode depending on the amplitude of the $\ell=3$ field ($\Delta_{33} \geq 0$). The rate of change λ converges like h^2 for various $\ell=3$ fields (h is the mesh size). The dependence of λ for the m=2, k=0 modes on the mesh size has been studied. The effect of an $\ell=3$ field on unstable m=2 modes is under consideration and will be discussed.

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Nonlinear propagation of electrostatic pulses. B.N.A. LAMBORN,[†] Dartmouth College. -- The collective coordinate representation for describing longitudinal plasma waves has been transformed into configuration space to facilitate comparison with the fluid equations of motion. The resulting equations of motion are expressed in terms of canonical variables. For one variable they are of the form

$$\dot{q} = \omega_p \, p(1-\beta \frac{\partial q}{\partial x})$$

$$\dot{p} = -\omega_p (q + \beta p \frac{\partial p}{\partial x})$$

$$\beta = (\omega_p Nm)^{-\frac{1}{2}}$$

The gradient of the first equation corresponds to the continuity equation and the second equation gives the fluid equation of motion for a cold plasma. These equations have both oscillatory solutions and soliton-like pulsed solutions corresponding to electron density disturbances that propagate in a uniform ion background.

†On leave from Florida Atlantic University.

NONLINEAR EVOLUTION OF RESISTIVE INTERCHANGE MODES IN A REVERSED FIELD PINCH*

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It has recently been demonstrated that certain Reversed Field Pinch configurations can be stable to tearing modes at zero β, and, when pressure is non-zero, can be stable against Suydam modes for values of central $\beta \approx 17\%$ [1]. These equilibria, however, are found to be unstable against pressure driven resistive interchange modes [2], which are just the odd modes of the slow interchange ordering of Coppi, Greene and Johnson [3]. Such modes can cause significant distortion of the flux surfaces. We use a non-linear, two-dimensional resistive MHD code [4] to study these modes for the case m=0, and present results pertaining to their non-linear evolution and saturation.

1. D. C. Robinson, submitted to Nuclear Fusion
2. D. C. Robinson, 8th European Conference, Prague, Vol. 1, 78 (1977)
3. B. Coppi, J. Greene, and J. Johnson, Nucl. Fusion 6, 101 (1966)
4. D. Schnack, UCRL-52399 (1978)

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Interaction of Tearing Modes

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A fully developed tearing mode modifies the magnetic field profile. We investigate the effect of this profile modification on linear growth rate of a different tearing mode.

First a simple slab model is investigated analytically. We find that the local flattening of the field profile drives adjacent modes more unstable by increasing the value of Δ'.

Next we study the effect of the saturation of the internal kink (m=1) mode on higher modes. The magnetic profile modification is based on Kadomtsev's[1] model for m=1 modes. We evaluate numerically the change in Δ' for higher m- modes, for a range of profile parameters. No significant change in the growth rate is found for realistic profiles.

1. B. B. Kadomtsev; Sov. J. Plasma Phys. Vol.1, 1975, p.389.

OPTIMIZATION OF THE $F(\psi)$ PROFILE IN TOKAMAK MHD EQUILIBRIUM CALCULATIONS*

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The MHD equilibrium equation, $\Delta^*\psi = -4\pi^2[\mu R^2 P'(\psi) + F(\psi)F'(\psi)]$, is typically solved for arbitrarily specified functions $P(\psi)$ and $F(\psi)$. Although early calculations usually took the functional forms of P' and FF' to be the same,[1] with the advent of "flux conserving" calculations, where $F(\psi)$ is determined from a specified $q(\psi)$,[2] it was found higher beta equilibria with reasonable properties could be obtained if the functional forms were different.[1,2] While specification of $q(\psi)$ is somewhat less arbitrary than specification of $F(\psi)$, it still must be noted that only $q(\psi_\ell)$ and, less accurately, $q(0)$ are known experimentally. Apart from these endpoints, the choice of $q(\psi)$ is still arbitrary, and the equilibria and corresponding stability are quite sensitive to the choice of $q(\psi)$.

It is conjectured, then, that the most physically resonable choice of $q(\psi)$ is that which minimizes the energy subject to given values of $q(0)$ and $q(\psi_\ell)$ for a given pressure. This should be the most stable equilibrium with these parameters, and it could be further conjectured that a real plasma would tend to set up fluctuations that would allow it to fall to this lowest energy state.

The results of minimization calculations for a cylindrical model are presented.

1. J. D. Callen and R. A. Dory, *Phys. Fluids* 15, 1523 (1972).
2. R. A. Dory and Y.-K. M. Peng, *Nucl. Fusion* 17, 21 (1977).
3. K. Evans, Jr., Argonne National Laboratory Report ANL/FPP/TM-98 (1977).

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

Stability in the Field-Reversed Mirror*

by

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An energy principle for the Vlasov stability of an axisymmetric field-reversed mirror is developed for magnetoacoustic perturbations. An assumption is made of an infinite conductivity electron background in spherical geometry. A sufficient condition for stability of m = 0 modes is given where the equilibrium distribution function is a function only of energy and canonical angular momentum. A physical interpretation of the stabilizing feature of the large-orbit system is the disappearance of ring-like poloidal energy surfaces and the appearance of quasi-ergodic orbits with loss of the third invariant.

*Work supported by DOE Contract #US Energy EY-76-S-02-2218.

Automated Calculation of Parametric Processes in Vlasov Theory

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and

Bernard Rosen, Stevens Institute of Technology

The method developed by the authors(1) for computing parametric decay rates for fluid modes has been extended to Vlasov theory by considering the velocity variable as a vector index. The method is illustrated by the calculation of the parametric decay rates of electromagnetic waves.

The algorithms have been implemented on the MACSYMA system.

(1) B. Rosen and H. Tesser, "Automated Calculation of Parametric Instabilities in Fluid Plasmas", to appear in Jrnl. Comp. Phys.

MODELING OF HIGH-β PLASMA DIFFUSION DUE TO LOW FREQUENCY MICROINSTABILITY*

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Low frequency instabilities like the lower hybrid drift instability or drift ion cyclotron instability have a strong influence on cross field plasma diffusion. In this paper, the various modelings of high-beta plasma and magnetic field diffusion due to the lower hybrid[1] and drift ion cyclotron instabilities[2] are described along with the numerical simulations. Our simulation models include, for the sake of comparison, the high-beta plasma diffusion due to the classical collision alone, the lower hybrid drift instability with the critical drift velocity cut-off[3], and the ion drift cyclotron instability along with the lower hybrid instability. These studies show the importance of the <u>correct</u> realistic modeling in the diffusion calculation.

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*Work supported by the Department of Energy.

1. R. C. Davidson, et al., Phys. Fluids 20, 301 (1977).
2. N. K. Bajaz and N. A. Krall, Phys. Fluids 15, 657 (1972).
3. J. P. Freidberg and R. A. Gerwin, Phys. Fluids 20, 1311 (1977).

MODELING OF SCYLLA IV-P END PLUG EXPERIMENTS

by

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Scylla IV-P end plug experiments[1] have been modeled numerically by a coupled hydrodynamic and heat flow method which includes radial and axial dynamics of the plasma column, time dependence of the external magnetic field, line and continum radiation losses, separate electron and ion temperatures and thermal conduction, thermal cross relaxation, flux limiting, and physical viscosity. Conduction, cross relaxation and viscosity are treated implicitly in time. This work is an extension of earlier end plug calculations by Malone and Morse[2]. Various calculated diagnostics including 5226 Å continum and total plasma energy line density are in good agreement with recent LiD plug experiments which showed a factor of x3 increases in energy containment time relative to open ended operation. Ion thermal conduction, flux limiting, and viscosity are found to be significant during the first few microseconds of an event. Higher Z plug materials give shorter energy confinement times, also in agreement with experiment. This is shown to be a consequence of line radiation loss and is in contrast with calculations without radiation loss which show energy confinement increasing with increasing Z for all Z.

[1]K. F. McKenna, R. J. Commisso, R. Conrad, C. A. Ekdahl and R. E. Siemon, Bull. Am. Phys. Soc. 22, 1079, Papers 213 and 214, (1977).

[2]R. Malone, and R. Morse, Phys. Rev. Lett. 39, 134 (1977).

Ergodic Behavior of Beam Orbits in Field Reversed Ion Rings

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We present numerical computations of beam orbits in a magnetic field modeling that of an axisymmetric field-reversed ion ring. Assuming that most beam orbits are of the large gyroradius type, we show that for reasonable beam temperatures, particle orbits are, loosely speaking, ergodic on most p_θ - H surfaces. That is, there does not exist a global third invariant. (For the field reversed mirror, on the other hand, few orbits are ergodic.) We show that, because of the ergodic nature of the orbits, resonant low frequency instabilities (Finn and Sudan, this conference) are present even in a beam of negligible spread in p_θ. We also discuss the effect of ergodicity on transport.

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Beam-Driven Instabilities in a Field-Reversed Ion Layer*

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We consider an infinitely long, thin, field-reversing ion layer immersed in a much denser, cooler, collisionless background plasma. The modes of the background plasma are examined for weak instabilities driven by the "beam ions" of the ion layer. (We do not consider modes for which the beam ions play an important part in the dispersion relation, e.g. precessional mode; nor do we consider instabilities driven by the gradient drifts of the background plasma, e.g. lower hybrid drift mode.) Most of the beam-driven instabilities which occur in plasmas without field-reversal are found to be stabilized in the presence of field-reversal because: 1) the beam velocity must be greater than the Alfven speed V_A for field reversal, and 2) some waves, as they travel across the ion layer, undergo mode conversion to heavily damped ion or electron acoustic waves, and 3) some waves do not have two turning points, and convect away from the ion layer. The only remaining candidates for beam-driven instability are the low frequency ($\omega << \Omega_i$) shear Alfven and magnetosonic modes. The worst of these modes have Im $\omega \sim \omega \sim V_A/a$, and $k_{||} \sim k_\perp \sim a^{-1}$, where a is the width of the layer. Even these modes can be stabilized by background ion and electron Landau damping, when β (of the background plasma) is sufficiently high, the layer is sufficiently short and fat, and the beam density is sufficiently low.

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Shear Stabilization of the Rayleigh-Taylor Modes†

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Rotating plasmas are subject to a centrifugal force which acts as an effective "gravity". This may give rise to a Rayleigh-Taylor instability when the force points in the direction of lower density, which is the case in the typical plasma containment experiment. On the other hand, shear in the flow may have a stabilizing effect if changing the flow pattern involves an increase in the kinetic energy.

In this work, a configuration suitable for the Tormac experiment or any rotating θ-pinch, is investigated analytically. It is remarkable that for suitable flows, the exact number of unstable modes can be determined analytically. Also, if the shear is large enough compared with the density gradient $(-\rho'\Omega^2/(r\rho\Omega'^2) < 3/4)^*$ the plasma may be completely stabilized.

* $()' = \frac{d}{dr}$, ρ = density, Ω = rotation frequency.

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Electron Heat Transport in Stochastic Magnetic Fields*

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The destruction of magnetic flux surfaces in tokamaks due to external perturbations or to short wavelength, finite β microinstabilities leads to enhanced radial particle and heat flux because of rapid particle transport along the stochastic field lines. We have developed a general theory for the calculation of transport coefficients in various stochasticity regimes.† In this paper we describe in detail the computation of electron heat transport in the physically important limit of weak radial localization of the modes, i.e., where the spectral width $\Delta k_{\|}$ is greater than L_K^{-1}, L_K being a mixing length for the magnetic turbulence and describing the rate of spatial divergence of adjacent lines.

The theory is based on well established and intuitive techniques of turbulence closure approximations. Heuristically, one computes the divergence rate of the lines, then finds the decorrelation time and length for particles moving along as well as diffusing across those lines. The diffusion coefficient then follows by standard random walk arguments. Systematically, we construct, then solve a kinetic equation for the joint probability distribution of particles and lines. The equation is more complicated than quasilinear theory (QLT). QLT considers the diffusion of typical single lines, thus misses the divergence of two lines in a typical pair. It predicts a diffusion coefficient which is significantly too small. Our theory includes the divergence effect. If z is the distance along a line, one finds that lines diverge as $\exp(z/L_K)$, where $L_K \equiv L_s(\frac{1}{2}\bar{k}_\theta^2 D_m L_s)^{-1/3}$, L_s is the shear length, $\bar{k}_\theta$ is a typical poloidal wavenumber, and D_m is the diffusion coefficient of the lines. The particle diffusion coefficient is then fully determined in terms of L_K, simple integral properties of the background magnetic turbulence, and the collisionality. We give the explicit formula for a reasonable model spectrum.

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†J.A. Krommes, R.G. Kleva, and C. Oberman, Abstract presented at this meeting.

Energy in the Linear Tearing Mode*

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We calculate the magnetic energy in the linear tearing mode for the slab mode. This is done by calculating the spatially averaged magnetic field to second order in the perturbation amplitude. It is found that in cases where the constant ψ approximation is valid, resistive effects are important outside of the resistive layer encountered in the first order analysis. These effects are important in resolving the apparently singular behavior of the magnetic energy in the external region. A somewhat surprising result of this calculation is that the perturbed magnetic energy density in the external region is positive, except in a small strip surrounding the resistive layer.

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Parallel Equilibrium Current in a Toroidal Plasma*

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The inclusion of resistive and viscous effects in the electron and ion fluid momentum equations permits the determination of the parallel current in a magnetically confined toroidal plasma. Using the expression for the neoclassical parallel viscosity previously derived,[1] the parallel current and conjugate Ware fluxes are determined for arbitrary values of $\xi_e = \mu_e/\eta_{||}$, where μ_e is the normalized electron viscosity coefficient and $\eta_{||}$ is the classical parallel resistivity. It is found that electron viscosity enhances the neoclassical resistivity $\eta_{||}^{nc} = \eta_{||}(1 + \xi_e)$ by providing an additional sink of momentum attributable to magnetic pumping of electrons in the poloidal field. Since μ_e remains finite for a toroidal plasma even in the absence of electron-ion friction ($\eta_{||} \rightarrow 0$), this result reveals the interaction of electron-electron collisions and trapped particles[2] to yield a conductivity reduction. For $\xi_e >> 1$ (due, for example, to trapped particle modes producing an anomolous viscous stress), the plasma poloidal rotation is surpressed and a finite (but small) $\beta_p \simeq 1$ results. The remaining electron and ion transport coefficients are also computed and evaluated in the banana regime for arbitrary cross sections and aspect ratios.

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[1] S. P. Hirshman Phys. Fl. 21, 224 (1978).

[2] B. Coppi and D. J. Sigmar, Phys. Fl. 16, 1174 (1973).

* Work supported by U.S. DoE Contract EY-76-C-02-3073.

STATUS OF NONLINEAR RESISTIVE MHD RESEARCH AT OAK RIDGE NATIONAL LABORATORY*

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Five main areas of the nonlinear resistive MHD program at ORNL will be discussed:

1) Generation of large magnetic islands in the single helicity approximation: Large $m = 2/n = 1$ magnetic islands can be produced when the current density falls fast enough near the limiter (there exists a cold layer). No flattening of the q-profile near the origin is required. The use of a new nonlinear code that employs the Fourier transform in the poloidal and toroidal directions (RSF) avoids the numerical problems associated with saturation of large magnetic islands in the MASS code. For comparable accuracy, the computer time required is in favor of RSF by a factor of 40 to 1.

2) Poloidal magnetic field fluctuations in tokamaks: It is shown with no free parameters that the amplitude of the Mirnov oscillations at the limiter and their scaling with total current can be explained in ORMAK and T-4 on the basis of nonlinear tearing mode theory. A semi-analytic model allows a possible correlation between the MHD activity and the presence of a cold layer near the limiter.

3) Major disruptions in tokamaks: Using the new code RSF, we can study the nonlinear interactions of tearing modes for higher values of S than before. We have been able to confirm the basic dynamical mechanism for destabilization of other modes by the 2/1 mode for the PLT profile with $S = 10^6$ at $r = 0$, ($S = T_R/T_A$). The fast time scale for the process is compatible with previous results. We have also studied a similar process for a T-4 q profile.

4) Magnetic field lines generated by tearing modes in Tokamaks: The possible ergodic nature of the field associated with overlapping $m = 2/n = 1$ and $m = 3/n = 2$ islands during the major disruption is presently being investigated.

5) Some preliminary results on feedback stabilization of tearing modes show the possibility of greatly delaying the $m = 2/n = 1$ magnetic island expansion at values of $S \sim 10^4$.

*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.

ANALYTIC COMPUTATION OF MINIMUM BETA AT IGNITION FOR VARIOUS TRANSPORT SCALING LAWS*

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A tokamak reactor must have an ignition point which is compatible with the constraints imposed by MHD stability. One important consideration in this regard is the achievable value of β. For a wide class of transport scaling laws, ignition is energetically possible only if β exceeds a specified value, denoted by β_{min}; β_{min} must be less than the upper bound on β consistent with MHD stability. For energy confinement times of the form $\tau_E \propto n\ T^j$, $j < 1$, we obtain algebraic relationships for β_{min} in terms of j and the parameters of the device. These results are then applied to a typical design using those scaling laws most commonly adopted in the reactor regime.

*Work supported by Department of Energy, Contract EY-76-C-03-0167, Project Agreement No. 38.

COUPLING OF SINGLE WAVEGUIDE RADIATION TO PLASMA WHISTLER AND LOWER HYBRID MODES*

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Several mechanisms can modify the plasma equilibrium so that the density gradient (∇n) is not perpendicular to the ambient magnetic field ($\underline{B}$). Examples are the nonlinear ponderomotive force due to radiation incident on a plasma from a spatially localized source, or the effects of a limiter. In this case, TE_{01} - radiation from a single waveguide can be effectively coupled into the plasma. Also, the wave refractive index ($n_{\|}$) parallel to $\underline{B}$ is no longer a constant along the ray trajectory, as in the $\nabla n \perp \underline{B}$, slab-geometry case. Thus an $n_{\|} = 0$ - wave in the vacuum can be transformed to a $n_{\|} > 1$ - wave within the plasma. Assuming $\nabla n \not\perp \underline{B}$, results from a sharp boundary plasma model and from a finite density gradient model, will be presented.

*Work supported by Department of Energy, Contract EY-76-C-03-0167, Project Agreement No. 38.

STABILITY THEORY AT INTERMEDIATE FREQUENCY* IN FUSION SYSTEMS

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This paper describes a detailed analytical study of the linear stability properties of plasma systems to drift waves in the frequency range from the lower hybrid ω_{LH} down to the ion cyclotron frequency ω_{ci}. This rather broad frequency range allows the study of systems with profiles ranging from very sharp $L_n \sim a_i$ to quite diffuse $L_n \sim a_i(M_i/m_e)^{1/2}$, where L_n is the plasma density scale length and a_i the ion gyroradius. Our reformulation of drift wave theory includes finite gyroradius for both ions and electrons, profile effects including electron and ion temperature gradients as well as density gradients, magnetic gradients and curvature and magnetic shear. The principal instabilities that we study are the lower hybrid drift instability at the high frequency end $\omega >> \omega_{ci}$, and the drift cyclotron instability at the low frequency end $\omega \approx \omega_{ci}$. The lower hybrid and ion cyclotron drift modes are particularly important, e.g., in the behavior of the linear theta pinch, the reversed field pinch, imploding liner devices and the sheath region of Tormac. In environments where the plasma evolves steep profiles into broad profiles, the unstable lower hybrid modes go over into drift cyclotron modes.[1] Important new results of the analysis for shearless systems include the fact that the instability condition for lower hybrid modes in terms of the various gradients and wavelength persists in the resonant drift cyclotron limit. We will discuss the instability criteria which indicate the importance of these modes over the entire frequency range in a variety of applications. In sheared magnetic fields, the effect of shear becomes less pronounced as the hybrid mode evolves toward the drift cyclotron mode despite the fact that the mode is becoming apparently more resonant. In the drift cyclotron limit shear becomes significant for $|L_s/L_n| < (M_i a_i/m_e|L_n|)^{1/2}$ where L_s is the shear length.

1. J. P. Friedberg and R. A. Gerwin, Phys. Fluids 20, 1314 (1977).

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

NEOCLASSICAL MODEL OF PARTICLE AND ENERGY BALANCE FOR EBT*

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An improved zero-dimensional or point model of particle and energy balance is formulated and applied to EBT in which all loss processes are assumed classical. The main improvement over earlier models is that the energy loss rates now include the average effects of temperature gradients as well as density gradients and the self-consistent ambipolar electric field. Thus we distinguish the particle confinement time from both the electron and ion energy confinement times. The earlier models simply used a single neo-classical loss rate taken to be the particle loss rate. Calculations for EBT-1 show the existence of a positive electric field branch and a collisional negative electric field branch. Highly collisionless positive field solutions are found to be thermally unstable while the stability of negative field solutions is found to depend on the neutral model. Stable negative field solutions are found for example when the total particle number density, plasma plus neutrals, is held fixed. Stable positive solutions are also found at intermediate collisionality. The negative field solutions are in qualitative agreement with experiment. Comparison is also made with the results of recent 1-D calculations done at ORNL. The model is used to project the performance of future EBT-S experiments.

*Work supported under contract with the Department of Energy.

ELECTRON EFFECTS IN ION-CURRENT FIELD REVERSAL*

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ABSTRACT

Existing calculations of ion-current driven field reversal have neglected all electron effects other than ion energy loss. The generation of a current by ionization of neutral-beam atoms is assumed to result from the charge separation induced by the magnetic field; all plasma currents are carried by the ions. However, electron currents can be generated by two means: 1) Electron-ion momentum transfer tends to equalize their average velocities, partially cancelling the ion current. This mechanism is particularly effective at a field null. 2) Radial electric fields are set up by the charge separation due to ionization or unequal transport rates. In these fields, electrons can drift in a way to cancel the ion current.

Electron currents in the presence of assumed ion species have been calculated using a simple model of electron-ion momentum transfer. We find the following general conclusions for an axisymmetric configuration: 1) The existence of a field null in steady state requires a net current at the null. This can arise in a plasma composed of more than one ion species having different charges and average velocities. Most simply, a non-rotating species offers a resistant background so that the electrons cannot accelerate to nullify the current of a rotating ion species. 2) Away from a field null, an azimuthal electron drift velocity arises only because of a radial electric field. 3) On open magnetic lines, electron end-conduction to grounded boundaries constrains the variation in potential to the order T_e/e. Azimuthal electron drift currents are small compared with the ion current and are justifiably neglected. 4) On closed magnetic lines, large potentials can develop between magnetic flux surfaces, and the possibility of significant cancellation of the ion current by drifting electrons exists.

A quantitative assessment of these effects requires a prescription for calculating electric fields and electron currents in ion particle codes, such as Superlayer at LLL. This is currently being implemented.

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NEUTRAL PARTICLE TRANSPORT IN MIRROR MACHINES: MONTE CARLO SIMULATION*

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ABSTRACT

A Monte Carlo code has been written to study the transport of neutral particles in mirror machine plasmas. Neutral particles emitted by simulated neutral beam sources are followed in three dimensions through a target plasma which is assumed to be in a steady state consistent with the neutral beam input. Ionization and charge exchange events are simulated using Monte Carlo techniques similar to those employed by Hughes and Post for Tokamak plasmas.[1] Descendent generations of incident neutral particles are followed until lost either through ionization or escape from the plasma.

At present the code uses a steady-state distribution of approximately 2×10^4 individual superparticles generated by the particle code, SUPERLAYER, as the target plasma, but an arbitrary target, given either in particulate or distribution function form, can be used.

Information available from the code includes: 1) flux of neutral particles into a detector, energy spectrum of the detected flux and mean position of charge-exchange events responsible for the detected flux, all as a function of detector scan position; 2) attenuation of neutral beams and fraction of beam power deposited in the plasma; 3) density and mean energy of neutral particles as a function of position; 4) neutral particle flux on and heating of a cylindrical wall surrounding the plasma as a function of position.

*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]M. H. Hughes and D. E. Post, Princeton Plasma Physics Lab Report PPL-1335 (1977).

Effect of Ellipticity on MHD Equilibria of Flux-Conserving Tokamaks*

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A theoretical investigation is carried out to determine the poloidal beta and other equilibrium parameters for a toroidal plasma with an elliptic cross section under the constraint of flux conservation[1] achieved by neutral beam heating. It is shown that the plasma pressure buildup during heating results from an outward shift in the magnetic axis and an elongation of the magnetic flux surfaces; a result which agrees with the conclusions of the computer studies of Dory and Peng[2]. We also find that the total plasma current increases with the pressure variable more dramatically for an elliptic cross section. This increase with ellipticity is, however, not quite as dramatic in the case of the variation of the poloidal beta with plasma pressure.

1. J. F. Clarke and D. J. Sigmar, Phys. Rev. Letters, 38, 70 (1977)
2. R. A. Dory and Y. K. M. Peng, Nuclear Fusion 17, 21 (1977)

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*Work supported by DOE

Multispecie Confinement in Tandem Mirror Reactors*

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The confinement characteristics of a multispecie plasma in a Tandem Mirror Reactor(1) are examined using a zero-dimensional, time dependent code that solves a set of self consistent particle and energy balance equations. For the electrons in the plugs we use the confinement times derived by Pastukhov(2), while for the ion confinement in these cells we utilize formulas we have derived using a simple binary collision theory whose results agree very well with Fokker-Planck calculations. Since the confinement of all particles in the solenoid is primarily due to the electrostatic potential, we have derived(3) a modified version of Pastukhov's results that apply to particle and energy confinement times in this region. We find that "Q" (ratio of fusion to injection energies) values of 4-5 are attainable for reasonable geometric configurations only if the alpha particles are selectively removed. We also find that this value of Q will be sharply reduced if the alphas along with other ions are allowed to undergo classical or anomalous (e.g., Bohm type) cross field diffusion.

1. T. K. Fowler and B. E. Logan, Comments on Plasma Physics and Controlled Fusion 2, 167 (1977)
2. V. P. Pastukhov, Nuclear Fusion 14, 3 (1974)
3. D. L. Galbraith and T. Kammash, Plasma Physics (To be published)

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*Work supported by DOE

NONLINEAR WAVE-PLASMA COUPLING AT THE LOWER HYBRID FREQUENCY*

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ABSTRACT

In order to study the problem of steady-state nonlinear wave-plasma coupling at the lower hybrid frequency, we derived a self-consistent nonlinear equation for the electric field of the slow mode at the plasma edge. Analytical solutions obtained for simple step models of the density profile enable us to compare results with those of the linear theory. At low amplitudes, results agree with those of linear theory. At high amplitudes, the ponderomotive force causes an evanescent region to be formed at the outermost edge, and significantly reduces the coupling efficiency.

*Work supported by the Department of Energy Contract No. EY-76-C-03-0167, Project Agreement No. 38.

TRANSPORT IN DOUBLETS*

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ABSTRACT

The 1-1/2-D GA transport code is used to study transport in doublet geometry. The transport equations are averaged over flux surfaces and then advanced in time numerically. Geometric quantities which arise from the flux surface averaging process are determined from 2-D MHD equilibria calculations. Iteration between transport and equilibrium calculation is performed to insure a self-consistent solution. The evolution of the plasma shape is determined by the programmed field-shaping coils and the assumed transport scaling laws. Several programming scenarios and scaling laws will be considered.

*Work supported by the Department of Energy, Contract No. EY-76-C-03-0167, Project Agreement No. 38.

KINETIC DESCRIPTION OF MHD BALLOONING MODE IN TOKAMAKS WITH GENERAL CROSS SECTION*

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ABSTRACT

A variational principle[1] derived from particle kinetic equations of motion is used to study the high toroidal mode number MHD ballooning mode[2] in tokamaks with general cross section. Near marginal stability, the mode rotates at one half of the ion diamagnetic frequency. The finite ion Larmor radius and perturbed electron pressure anisotropy are stabilizing effects; whereas the perturbed ion pressure anisotropy and the longitudinal electric field are destabilizing. Depending on the mode number, the mode frequency can be either in the trapped ion regime or flute ion regime. The lowest threshold value of beta occurs at the low frequency end of the flute ion regime. The dominant additional destabilizing feature is the coupling of the perpendicular motion to the longitudinal electric field. The Euler equation for the mode structure along the field line is derived and solved numerically. The critical beta obtained from the kinetic variational principle will be compared with that from MHD.

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INDUCTION OF FORCE-FREE CURRENTS BY BOUNDARY DISPLACEMENTS IN A SCREW PINCH*

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The main plasma column in a screw pinch under equilibrium will expand or shrink with further heating or cooling. When force-free currents are present in the region between the main plasma column and the outer wall, this column motion represents a moving inner boundary to the low density plasma carrying the force-free currents, and the force-free currents will grow or decay as a result. A theory suitable for this problem is presented to describe the time evolution of these force-free currents. A set of conservation equations is derived for the magnetic fields, and an ordinary differential equation is obtained from the force-free condition for the plasma velocity. The magnetic fields obtained from these equations are uniquely determined by the displacement of the inner boundary, regardless of the velocity of this boundary; but the plasma velocity is of course completely determined by this boundary velocity. Both analytical and numerical solutions are presented for representative cases to demonstrate this induction effect.

* Work supported by U.S.D.O.E. under contract EY-76-S-02-2456.

TRANSPORT AND RADIATION STUDIES OF BELT PINCHES AND HIGH-BETA TOKAMAKS*

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Transport and radiation studies are performed for 2:1 ratio elliptical cross-section plasmas, using the two-dimensional diffusion code G2M. The Torus I and II machines at Columbia are used as models. From the viewpoint of radiation, these machines represent the general classes of cold pinch-tokamaks (10-20 eV) and hot pinch-tokamaks (50-100 eV), which are qualitatively different because of oxygen impurities. Two types of profiles are studied: parabolic density and temperature distributions, and force-free current profiles, with density peaked near the center and temperature almost flat.

For the cold machines, small amounts of oxygen cause near-uniform decrease of temperature throughout the profiles. Power balance shows radiation to dominate all other losses. The toroidal field distribution often becomes paramagnetic, agreeing with the Maryland TERP experiments. For the hot machines at 100 eV, the profiles cool slowly, with other losses comparable to radiation. At 50 eV, a qualitative difference appears between the parabolic profiles and the force-free current profiles. In the former, the outer edges cool more rapidly, and eat into the core of the profile. In the latter, the outer regions (at lower density) remain hot, while the center cools and gives a hollow temperature profile. The decay of the plasma toroidal beta, however, is much slower in the latter profiles.

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Spatial Structure of the Beam Driven $2\omega_{ci}$ Mode

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Abstract

In previous work[1], it was found that the slow wave at $2\omega_{ci}$ could easily be destabilized in an infinite homogeneous deuterium beam plasma system. The effects of magnetic shear and particle density variations on this mode are studied here. Three important questions are addressed: is the mode radially localized by magnetic shear; is the mode localized along the magnetic line of force by the variation of $|B|$; and is there linear mode conversion between this mode and the fast (magnetosonic) mode inside the plasma. The radial structure is found to be proportional to $\exp(-i\sigma_\perp x^2/2)$ with $\sigma_\perp \sim (\rho_i L_s)^{\frac{1}{2}} (v_{b\perp}/v_e)^{\frac{1}{2}}$. The mode is localized along the field line with length of the order of $(L_B v_e/\omega_c)^{\frac{1}{2}}$. The mode coupling problem studied is central for understanding the emission from beam driven tokamak plasmas. In addition it is the inverse problem to the usual ICRF heating problem in which the fast mode converts to the slow mode.

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Localized Trapped Electron Drift Instability

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Abstract

Using the full electron dynamics including temperature gradients in the electrostatic collisionless drift wave radial mode equation $\varphi'' + Q(x,\omega)\varphi = 0$, where φ is the fluctuating potential, we find two distinct even parity eigenmodes, which are localized well within the acoustic turning point, and hence do not need ion dynamics for localization. <u>The modes are unchanged by the presence or absence of the acoustic term in $Q(x,\omega)$.</u> This happens because the temperature gradient terms in $Q(x,\omega)$ provide a well near the mode rational surface for the localization of the mode. Inclusion of trapped electrons in $Q(x,\omega)$ drives these modes strongly unstable. Since these modes are more localized than the conventional trapped electron mode, i.e., the drift-acoustic mode, the toroidal mode coupling is unimportant for a larger range of shear and azimuthal mode number. Analytical and numerical results, which are in very good agreement, are presented; these include the radial structure of the mode, the variation of the growth rate with shear and radial mode number, etc. The importance of these strongly growing modes for current and future tokamaks is considered. We believe that these are the first reported localized drift modes which do not depend on the ion acoustic localization.

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Numerical Calculation of Impurity Diffusion in Tokamaks

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Abstract

Two transport codes have been developed to solve the equations describing the simultaneous diffusion and ionization-recombination of several impurity states in a tokamak plasma. The impurity diffusion is assumed to be in the Pfirsch-Schluter regime and the full diffusion coefficient matrix is retained in both codes. Code 1 uses a spline Galerkin method in which the unknown functions are expanded in terms of cubic splines on a non-uniform knot sequence. Code 2 uses a collocation scheme with Hermite cubic splines as the trial functions with the unique feature that each function is expanded on a different dynamically changing knot sequence. A model problem has been examined in which oxygen or carbon is allowed to diffuse into a plasma determined by programed n_e and T_e profiles. The total radiation from each state is computed. One interesting feature of the results is that for long times the maximum oxygen concentration is not at the center.

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INTERNAL KINK INSTABILITIES IN REVERSED FIELD PINCHES*

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This paper investigates the MHD stability properties in reversed field pinch (RFP) configurations. The maximum growth rates (γ^2) of the internal m=1 kink modes can generally be separated into three types, depending on the radial location r_s of the singular surface $[\underset{\sim}{k}\cdot\underset{\sim}{B}\,(r_s) = o]$. We denote these by: (1) $\gamma_o{}^2$, for interchange-like modes, where the singular surface is near the axis ($r_s \sim o$), (2) $\gamma_{\overline{W}}{}^2$, for the Robinson modes[1], where the singular surface locates near the wall ($r_s \sim R$), and (3) $\gamma_S{}^2$, for the generalized Suydam modes, where r_s lies between the axis and the wall. Making use of local stability analyses, a detailed parameter survey is presented which shows that the internal kink mode growth rates are reduced by increasing the following relevant quantities:

(1) $\gamma_o{}^2$ is decreased by increasing $I \equiv 2\left(\frac{B_\theta}{r}\right)^2 \left[\frac{d^2P}{dr^2} + 2\left(\frac{B_\theta}{r}\right)^2 \frac{\gamma P}{\gamma P + B^2}\right] \Big|_{r=0}$,

(2) $\gamma_{\overline{W}}{}^2$ is decreased by increasing $\overline{W} = -\,\mu(r=R)/\mu(r=o)$, where $\mu \equiv \dfrac{B_\theta}{rB_z}$,

and (3) $\gamma_S{}^2$ is decreased by increasing $S = 1 + 8\,\dfrac{\frac{dP}{dr}}{rB_z{}^2}\left[\dfrac{\mu}{d\mu/dr}\right]^2$.

The dependence of growth rates on the choice of equilibrium profiles is examined both analytically and numerically in an effort to determine those equilibrium profiles with optimum stability properties. Emphasis in these studies is placed on RFP systems with parameters analogous to ZT-40 experiment. The present analysis is part of a more complete study of the sensitivity of MHD stability property to variations in the equilibrium profiles for RFP configurations.

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A KINETIC STUDY OF NON-LINEAR SATURATION OF TRAPPED ION MODES BY MODE COUPLING

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A kinetic derivation is given for the non-linear coupling of trapped-ion modes in Tokomak geometry. This is done by a systematic resolution of Vlasov equation order by order in $\frac{\omega}{\Omega_c}$, to second order in the perturbed potential.

All important kinetic effects are incorporated (temperature gradient, magnetic gradient drifts, realistic collision operator, Landau damping), but turbulent detrapping is neglected, assuming $\frac{e\phi}{\varepsilon T} \ll 1$ where ϕ is the perturbed potential and ε the inverse aspect ratio of the torus. Then a full non-linear dispersion relation is established, valid in all collisionality regimes and for any value of the magnetic gradient and temperature gradient drift frequencies. This equation involves full integration in velocity space, and takes into account the mode structure along magnetic field lines. In a simple case ($\omega_D = |\vec{\nabla} T| = 0$, $\nu_{ie\ell} \ll \omega \ll \nu_{ee\ell}$) it confirms the coupling coefficients derived by Laquey et al. from Kadomstev and Pogutse's four-fluid model. This is done by keeping only the dominant non-linear term, establishing a quadratic form and performing the velocity integrals with a test function for the mode structure along magnetic field lines.

Solving this equation in various regimes is then only a matter of taking into account the linear characteristics of the instability in the domain of paremeters considered. First results are given in various cases ($\vec{\nabla} T \neq 0$, $\omega_D \neq 0$, weak collisions...).

This work is valid only for one-dimensional modes ($k_x = 0$) or for convective modes with constant wave numbers. Work is in progress to take into account the radial structure of modes localised by rational magnetic surfaces, thus providing a full investigation of mode coupling in two dimensions.

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KINETIC APPROACH TO THE PONDERMOTIVE EFFECTS IN A PLASMA*

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In plasma heating with high-power wave-sources, the distribution function of the particles is significantly modified by the pondermotive force. A kinetic theory of such phenomena is needed in order to understand the full phase-space evolution of the coupling and heating.

From nonresonant quasilinear theory we derive the kinetic equation for the slow-time varying part of the distribution function. The equation is valid for an externally excited coherent wave with a spatially dependent amplitude in three-dimensional unmagnetized plasmas. This is a generalization of the one-dimensional problem, recently published.[1] The steady state solution for the time averaged distribution function is obtained to second order in the electric field amplitude. It shows the usual density self-modulation and a new anisotropic change of "temperature". The anisotropy in this apparent temperature is due to the nonresonant diffusion and leads to an unstable electromagnetic mode.

The method is applicable to a magnetized plasma. In the case of very large field amplitudes, a new nonperturbative approach to the Vlasov equation will be described.

* Work supported by National Science Foundation (Grant ENG 77-00340) and U.S. Department of Energy (Grant EG 77-G-01-4107).

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LOWER-HYBRID-DRIFT INSTABILITY IN LINEAR FUSION SYSTEMS WITH REVERSED MAGNETIC FIELDS*

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Such emerging fusion concepts as reversed-field theta pinches,[1] reversed-field mirrors,[2] and liner implosions of reversed-field plasma configurations created by transient relativistic electrons beams[3] have raised the question of the microinstability and transport properties of such reversed-field systems. We consider several important features of the lower-hybrid-drift instability[4] in reversed-field geometry.

First, we consider electrostatic perturbations about a field-reversed equilibrium using a hybrid model with kinetic ions and cold-fluid electrons ($T_e \to 0$). To describe the physics in the vicinity of the field null ($B \to 0$), the electron model incorporates inertial effects ordinarily neglected in treatments of the lower-hybrid-drift instability. A local stability theory is developed that tracks the instability behavior through the B=0 field null. As $B \to 0$, we find $\omega \simeq \omega_{ce}/\sqrt{3}$ (locally), with negligibly small growth rate. Second, a nonlocal stability analysis for a cylindrical plasma equilibrium with a maximum in $-\partial \ell nN/\partial r$ at $r=r_M$ existing outside the field reversal point finds lower-hybrid-drift eigenmodes localized within a distance $(m_e/m_i)^{1/4} L_N$ about $r=r_M$.

Finally, finite beta effects are examined using an electromagnetic kinetic local stability analysis that includes ∇B_0 orbit modifications. Although this model does not incorporate all electron inertial effects that might be important near B=0, it is found that finite beta effects are strongly stabilizing, particularly when $T_e/T_i \sim 1$.

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WARM PLASMA EFFECTS ON THE DCLC MODE*

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The drift cyclotron loss cone instability is considered to be one of the more dangerous instabilities in a Mirror machine. Recent experiments have shown that injection of a warm plasma stream can have a strong stabilizing effect on this mode. We perform a numerical stability analysis which studies in detail the evolution of the unstable spectrum as the loss cone is filled with a warm Maxwellian component. We find that the broadband spectrum present in the absence of the warm component develops a complicated banded structure and the real frequency occurs at discrete harmonics of the ion cyclotron frequency. Under certain conditions, it is found that the lowest harmonics have the largest rate of growth.

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SATURATION OF PARAMETRIC DECAY OF LOWER HYBRID WAVES INTO ION CYCLOTRON WAVES IN INHOMOGENEOUS PLASMAS

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On account of finite density gradient, the parametric decay of lower hybrid waves into ion cyclotron waves of long parallel wavelength possesses quite low threshold and predominates at moderate powers. The instability is stabilized by the self induced modification in the ion gyrofrequency (by the ion cyclotron wave) which detunes the three wave resonance. This gives rise to $\omega^{-3/2}$ spectrum of ion cyclotron waves which seems to explain the observed spectrum at General Atomic.

*Work supported by NSF and Office of Naval Research.

Continuous Operation of Tokamak Reactors with RF-Driven Currents*

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We suggest the injection of net momentum RF waves into a tokamak plasma to permit steady-state reactor operation.[1] We note that high phase velocity waves can establish continuous toroidal currents that are primarily carried by relatively fast electrons, effectively diminishing the plasma resistivity. Currents sufficient for plasma confinement in reactors operating near $\beta_p = R/a$ may be achieved at a power cost

$$P_D = \left(\frac{4 P_f}{w^2}\right)\left(\frac{10^{14}\,\mathrm{cm}^{-3}}{n}\right)^{1/2}\left(\frac{10\,\mathrm{keV}}{T}\right)^{1/2}\left(\frac{\mathrm{meter}^2}{aR}\right)^{1/2},$$

where P_f is the fusion power density for D-T reactions near 10 keV and w is the wave phase velocity normalized to the thermal velocity. Typical reactor parameters allow P_D/P_f small, implying acceptable power dissipation in RF-driven reactors, a conclusion previously thought false because of the incorrect modeling of the current as a single electron fluid.[2] A particularly attractive possibility is the generation of the current by lower hybrid waves, which can penetrate the plasma center while dissipating a significant fraction of the incident power. We also show that demands on waveguide capabilities are modest and deleterious nonlinear effects are unlikely.

* Work supported by U.S. Department of Energy (Grant EG 77-G-01-4107).

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<u>SPUDNUT - A Fast Neutral Transport Routine</u>.*-- K. Audenaerde, G. Emmert, and M. Gordinier, <u>University of Wisconsin, Madison</u>.

The transport of neutral hydrogen-like particles in a plasma with reactor parameters has been studied using a statistical transport model. Slab geometry was used, and charge exchange sources are thought to be concentrated at the meshpoint inside each slab and supposed to be monoenergetic at the local temperature.

An integral equation for the charge exchange source is developed and transformed into a discretized system which rigorously conserves particles and energy[(1)]. This system is solved exactly by a single matrix inversion. From the solution for the charge exchange source one calculates the energy transfer from the neutrals to the plasma, the local ionization rate and the flux of neutrals (and their spectrum) to and from the wall. Reflections at the wall are incorporated, using data from Oen and Robinson[(2)].

Results compare favorably with ANISN (PPL)[(3)] and FASTSLAB (ORNL)[(4)] calculations; SPUDNUT is extremely fast, using about .1 sec CPU-time on the MFE CDC-7600 computer.

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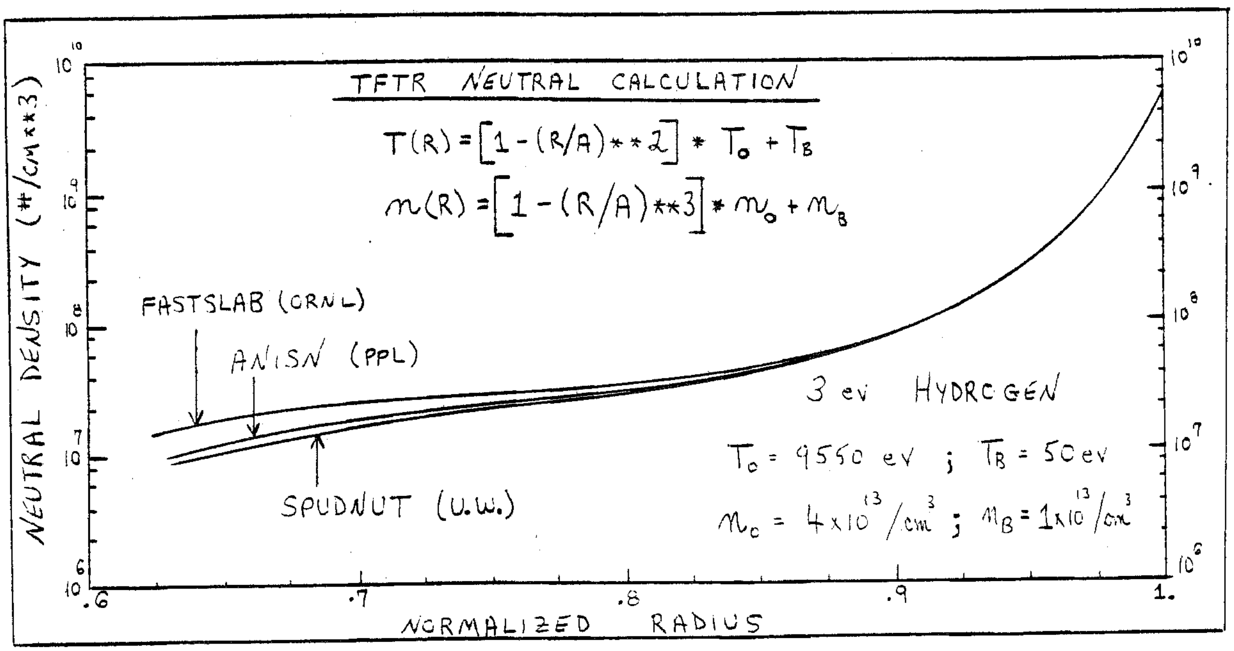

EFFECT OF SHEAR ON DCLC MODE*

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We have investigated the effect of shear on the drift cyclotron loss cone mode for a model where the ions are treated in the straight line orbit approximation. Our analysis is valid for scale lengths comparable and even greater than an ion Larmor radius and for finite beta, provided that the electrons are cold. We find that shear is destabilizing at low beta and long wavelengths. For $\beta \sim 1$, shear is stabilizing, but quite large shear scale lengths are needed for stability. Detail plots will be presented.

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NUMERICAL MODELING OF PLASMA HEATING IN TORMAC*

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A numerical study of plasma heating in Tormac has been undertaken using a 1D hybrid code.[1] Initial runs have been carried out in slab geometry. In present experiments, a stabilized pinch is created in the chamber, followed by application of the Tormac cusp field. Attention has focused on heating as the cusp is applied. The advantage of this code is that in addition to ohmic heating and adiabatic compression, ion diffusion and ion heating due to reflection from the imploding cusp can be studied. Also, any anomalous resistivity associated with instabilities, e.g. lower hybrid drift,[2] is obtained self-consistently.

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SIMULATION OF LOWER HYBRID HEATING OF A NONUNIFORM PLASMA*

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A computer simulation is used to study the collective processes which are expected to occur in a nonuniform plasma when driven by RF sources in the lower hybrid frequency range. This work uses an electrostatic particle simulation code developed earlier[1] which models a $2\frac{1}{2}$ dimensional, magnetized plasma slab, periodic in one direction and bounded in the other, with a vacuum-plasma boundary along which various excitation sources are located. In this study, the zero order density increases away from the RF source across a uniform magnetic field, and the exciter consists of two capacitor plates oscillating out of phase. Those wavenumbers which experience small electron Landau damping are observed to penetrate to the lower hybrid layer. Correlation measurements are used to identify the propagation characteristics of the various waves traveling across the magnetic field. Nonlinear effects at the low density edge near the antenna are found to be important. Some of the related observations include the creation of ion bursts near the antenna, which proceed to diffuse through the plasma, and electron heating at the plasma surface. The spatial distribution of the plasma heating is being investigated.

*Work supported by USDOE and ONR.

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Zero Electron Mass Plasma Simulation in Two Dimensions*

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Zero electron mass hybrid simulation methods in r-Z coorinates are being developed for application to a variety of fusion plasma studies. The simulation algorithms make use of Ohm's law to provide the electric field in regions of finite density assuming $N_e \simeq N_i$; and $M_e = 0$. The magnetic field and the associated electron current are determined by functional iteration of the Darwin limit of Faraday's law. Fields in the vacuum region between the plasma and the wall are provided by SOR iteration of the vacuum field equations. These techniques are capable of describing the strong inhomogenities found in macroscopic studies of such phenomena as the plasma focus and θ-pinch endloss. A description of the algorithm as well as preliminary results will be presented.

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Numerical Simulation of the Tormac Experiment*

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By means of numerical calculations, we seek to understand the effect of the magnetic field geometry on the confinement properties of the Tormac experiment.

The experiment is modelled on a two-dimensional, axisymmetric domain by the equations for time-dependent, magnetohydrodynamic flow with anistropic resistive diffusion. The domain is periodic in z, with conducting boundaries at r=a and r=b, b>a.

The magnetic fields in the domain include a toroidal field and a poloidal field with periodic line cusps created by fixed toroidal conductors. A toroidal, high-beta plasma is confined on closed magnetic surfaces, and its pressure is supported by a sheath separating it from the poloidal field. Initially, the plasma is not in equilibrium but in a relatively short time moves into its equilibrium configuration.

Plasma confinement is determined by the lifetime of the plasma in the sheath and by the diffusion of plasma from the confinement region into the sheath. The loss of plasma from the sheath is determined in the calculations by mass decay in an annihilation region near the cusps in the poloidal field. When mass decay time is short, the plasma pressure at the cusp is small, and the sheath plasma will flow along poloidal field lines to a cusp as in a linear theta pinch. When the decay time is long, the plasma pressure will be essentially constant along field lines in the sheath. The two-dimensional diffusion into the sheath is modelled by transport with classical dependence on the plasma parameters, but with a variable anomaly factor.

The dependence of plasma confinement on the decay time and the anomaly factor is examined.

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Magnetoacoustic Heating of a Collisionless Pinch*

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The effect of finite ion gyroradius on magnetoacoustic heating of a sharp-boundary screw pinch is being studied theoretically and the results are being applied to cases of experimental interest. The theoretical calculation is based on the Vlasov-fluid model[1] in which collisionless ions and massless, fluid electrons are treated under the assumptions of quasi charge neutrality and negligible displacement current. In order to take proper account of the sharp boundary, the starting equations are those derived by Lewis and Turner for applying the Vlasov-fluid model to a sharp-boundary screw pinch.[2] Within the pinch the collisionless Boltzmann equation for the Vlasov-fluid model has been solved analytically for small values compared to unity of kr_L and ω/ω_{ci}, where k is the largest relevant wavenumber, r_L is the ion gyroradius, ω is the frequency, and ω_{ci} is the ion cyclotron frequency. Finite-ion-gyroradius effects were kept to zeroth and first order and the solution is valid up to the sharp boundary. Because this approach uses a general ordering, it also should be possible to determine whether dissipative mechanisms other than Landau damping are operative for magnetoacoustic heating in a collisionless plasma. A differential equation for $\underset{\sim}{\xi}$ ($\underset{\sim}{A}^{(1)} = \underset{\sim}{\xi} X \underset{\sim}{B}^{(0)}$) containing finite gyroradius effects was derived by substituting the solution of the collisionless Boltzmann equation into the transverse force-balance equation (the component perpendicular to $\underset{\sim}{B}$ of the Maxwell $\underset{\sim}{\nabla} X \underset{\sim}{B}$ equation). An analytical solution of the equation for $\underset{\sim}{\xi}$ was used to calculate the heating of the pinch in the presence of an oscillatory driving electric field on a cylindrical surface in the vacuum region surrounding the pinch. When there is a finite longitudinal wavelength ($k_z \neq 0$), significant additional heating can occur as a result of finite ion gyroradius. Illustrative numerical examples of enhanced heating computed with this approach will be presented.

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A General Two-Dimensional Tokamak Model

by

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A two-dimensional Lagrangian computer simulation model of tokamak discharges is used to investigate the time evolution of a finite conductivity plasma in a finite conductivity vessel. The calculation of the time development of the discharge is based on the quasi-static evolution of pressure balance in the plasma. This code is unique in that it is designed to follow both the resistive diffusion and gross dynamics of the plasma, as well as vacuum and conducting-shell regions of the discharge.

The Lagrangian coordinate system uses a general-connectivity triangular grid which permits accurate treatment of problems of much greater complexity than conventional, one-dimensional schemes. Specifically, non-circular plasmas (elliptical or D-shaped) and multiple magnetic axes including separatrices and magnetic divertors may be studied.

The physical system of interest is the cross-section of a toroidal conducting shell optionally containing internal conductors. The present model is based on the assumption that the quasi-static pressure balance equation ($\nabla p = \frac{1}{c} \underline{j} \times \underline{B}$) is always satisfied. The model incorporates the diffusive fluxes of material, energy and magnetic fields.

Results will be presented which illustrate the tesselation of magnetic surfaces and the equilibrium states of circular tokamak, Doublet and divertor discharges. The dynamic behavior will be demonstrated by the outward movement (toward the limiter) of the plasma flux surfaces of a circular tokamak discharge as the poloidal beta is increased from a very small value to a value of order one.

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Resonant Instabilities of a Field-Reversed Ion Ring*

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Low frequency MHD stability of field reversed ion rings in a background plasma is studied. The background ion and electron species are treated by fluid equations, whereas the beam is treated by kinetic theory. The energy principle of Sudan and Rosenbluth[1] is used with both the resonant and nonresonant parts of the beam energy computed in terms of an autocorrelation function of the beam orbits. For a mode with variation $\delta\underset{\sim}{B} \sim \exp(i\ell\theta - i\omega t)$ along the symmetry direction, resonances with the betatron frequencies ω_β of the beam, $\omega - \ell\langle\dot{\theta}\rangle \pm \omega_\beta = 0$, occur. It is found that these resonant effects can lead to instability for waves whose phase velocity is in the same direction as the beam current. Waves whose phase velocity is opposite to the current are damped. Thus the beam breaks the degeneracy of a stable MHD mode of the background plasma. Since the beam also leads to a change in the real part of the frequency of the mode, we recognize the possibility of stabilization due to resonances with the background plasma. In addition, the instability is discussed for parameters pertinent to a field-reversed mirror.

*Work supported by U.S. Department of Energy Contract #EY-76-S-02-3170.

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Beam-Driven Instabilities in a Field-Reversed Ion Layer*

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We consider an infinitely long, thin, field-reversing ion layer immersed in a much denser, cooler, collisionless background plasma. The modes of the background plasma are examined for weak instabilities driven by the "beam ions" of the ion layer. (We do not consider modes for which the beam ions play an important part in the dispersion relation, e.g. precessional mode; nor do we consider instabilities driven by the gradient drifts of the background plasma, e.g. lower hybrid drift mode.) Most of the beam-driven instabilities which occur in plasmas without field-reversal are found to be stabilized in the presence of field-reversal because: 1) the beam velocity must be greater than the Alfven speed V_A for field reversal, and 2) some waves, as they travel across the ion layer, undergo mode conversion to heavily damped ion or electron acoustic waves, and 3) some waves do not have two turning points, and convect away from the ion layer. The only remaining candidates for beam-driven instability are the low frequency ($\omega \ll \Omega_i$) shear Alfven and magnetosonic modes. The worst of these modes have Im $\omega \sim \omega \sim V_A/a$, and $k_{||} \sim k_\perp \sim a^{-1}$, where a is the width of the layer. Even these modes can be stabilized by background ion and electron Landau damping, when β (of the background plasma) is sufficiently high, the layer is sufficiently short and fat, and the beam density is sufficiently low.

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High Frequency Convective Loss-Cone Instability in Short Mirror Machines*

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The high frequency convective loss cone mode is found to be absolutely unstable, due to exponentially small reflection from the mirror throats, whenever

$$\beta \gtrsim (m_e/m_i)(m_e c^2/T_i)^{2/3}$$

and $L_p/\rho_i \gtrsim \beta^{-1/2}$

and $\Delta << 1$

where L_p is the axial plasma scale length, ρ_i is a thermal ion Larmor radius, and Δ is the fraction of warm plasma streaming through the mirror machine. (The condition on L_p/ρ_i is equivalent to requiring that the plasma be at least as long as the shortest axial wavelength, an instability condition derived previously.[1]) Even when $\beta < (m_e/m_i)(m_e c^2/T_i)^{2/3}$, gradual tapering of the mirror throats, viz.

$$L_m/L_p \gtrsim \max(\Delta^{-1/2}, \omega_{pi}/\Omega_i)$$

(where L_m is the distance between the mirror throats, the plasma density being a Lorentzian function of axial position between the mirror throats), and large radial scale length

$$R_p/\rho_i \gtrsim \omega_{pi}^2/\Omega_i^2$$

are needed to avoid instability.

These results differ from those of some previous calculations[2] (which did not consider modes with $k_\perp\rho_i << (m_i/m_e)^{1/2}$), and appear to preclude designing a linearly stable mirror fusion reactor with nearly empty loss cone.

*Research supported by U.S. Department of Energy Contract #EY-76-S-02-3170-1.

1. H. L. Berk, L. D. Pearlstein, and J. G. Cordey, Phys. Fluids 15, 891 (1972).

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An Exactly Soluble Model for Reconnection†

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The breaking and reconnection of magnetic field lines has been a durable problem in astrophysics, where the mechanism is believed to be fundamental to the understanding of solar flares and other phenomena. In the laboratory, reconnection is realized in tearing modes. A few models were suggested to describe this phenomenon. They usually involve approximations like boundary layer assumptions, dropping of certain terms in the equations, etc. When exact solutions to the equations were produced, they contained unphysical features like expansion shocks or other singularities.

We can produce an exact and valid solution to the full set of equations. Its features are:

1. Compressible or incompressible ideal MHD equations are used.
2. The process is not coplanar. Two streams carrying anti-parallel fields collide, the fields rotate and reconnect.
3. The solution is composed of constant state regions, separated by Alfven (rotational) and slow shocks.
4. In the incompressible case, the projection of all fields and velocities on the reconnection plane, yields a configuration identical to the one given by Sonnerup - including the numerical values he obtained, except for the jump in the pressure.
5. The maximum rate of reconnection is lower, and the final flow velocity is larger, than those predicted by the model in Ref. 1.

1. B.U.O. Sonnerup, J. Plasma Phys. 4, Part 1 (1970).

† Work supported by U.S. DOE, Contract No. EY-76-C-02-3077.

Feedback Stabilization of Tearing Modes in Tokamaks*

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Large amplitude tearing modes in Tokamaks can contribute significantly to radial transport. Furthermore the major Tokamak disruption, which limits the high density, low q, and large $n\tau$ operation of Tokamaks, is preceeded by a precursor oscillation which is identified as a m = 2 tearing mode.[1,2] For these reasons feedback stabilization of this mode seems desirable. We have numerically investigated a stabilization procedure which appears to be experimentally feasable.

In terms of the linear theory of the mode, the stabilization is easily understood. The mode involves a perturbed field $B_r(r) \cos m\Theta$ which has a discontinuity in its radial derivative $\Delta' = (B'_{r+} - B'_{r-})/B_r$ across the island. The growth rate is proportional to Δ' and thus it is simply necessary to modify the boundary conditions for B_r through auxiliary coils so as to produce $\Delta' = 0$. The detection of the mode can be performed with magnetic pickup loops or using x-ray emission, which is simpler in that the feedback signal cannot be confused with the initial mode.

Including diamagnetic effects, which cause the mode to rotate, we have verified that this procedure can give stabilization at any desired amplitude, and have been able to derive a simple model which reproduces the essential results of our code. The necessary coil current to stabilize an island at a width of a few percent of the minor radius is on the order of one kiloamp (for PLT) and the necessary coil response time is well within experimental capabilities. Methods of producing stabilization using a random phase signal are being pursued.

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CONTINUOUS TOKAMAKS*

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We propose a tokamak configuration that permits the rapid replacement of a plasma discharge in a "burn" chamber by another one in a time scale much shorter than the elementary thermal time constant of the chamber first wall. With respect to the chamber, the effective duty cycle factor can thus be made arbitrarily close to unity minimizing the cyclic thermal stress in the first wall. At least one plasma discharge always exists in the new tokamak configuration, hence, a <u>continuous tokamak</u>. By incorporating adiabatic toroidal compression, configurations of <u>continuous tokamak compressors</u> are introduced. To operate continuous tokamaks, it is necessary to introduce the concept of mixed poloidal field coils, which spatially groups all the poloidal field coils into three sets, all contributing simultaneously to inducing the plasma current and maintaining the proper plasma shape and position. Preliminary numerical calculations of axisymmetric MHD equilibria in continuous tokamaks indicate the feasibility of their continued plasma operation. Advanced concepts of continuous tokamaks to reduce the topological complexity and to allow the burn plasma aspect ratio to decrease for increased beta are then suggested. Comparisons with conventional tokamaks are made in the light of reactor applications, indicating several potential advantages of some <u>advanced continuous tokamaks</u> that require comparable toroidal magnetic field energy to produce comparable fusion power.

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SIMULATION MODELS FOR EFFECT OF RF TURBULENCE ON 2XIIB*

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ABSTRACT

An improved Monte Carlo[1] model of the effect of RF turbulence generated by the DCLC mode has been incorporated into the Superlayer particle simulation code. Diffusive effects of the turbulence on ion energy and velocity phase and the associated spatial transport have been studied in the density regime of 2XIIB. Plasma electrons have been treated as a pressureless background which carries no current, but neutralizes the ions electrostatically and exerts a drag on them. This is felt to be appropriate for the open-field-line cases to which we have devoted most of our efforts.

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SIMPLE ROTATING FIELD REVERSED PLASMA EQUILIBRIA*

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ABSTRACT

Rotating equilibria, such as are generated in the LASL reversed field theta pinch, are surveyed as a function of five parameters: plasma beta, pressure profile, rotation velocity, aspect ratio of the theta pinch, and the mirror ratio of the vacuum field. Several models have been examined, the simplest of which is the one fluid, scalar pressure, rigid rotator model. The equilibrium is described by two equations: a Bernoulli type relation between the density, ρ, and the electric potential $\phi(\psi)$, (C_s - sound speed)

$$B\cdot\nabla\left[C_s^2 \ln\rho - \frac{r^2}{2}\left(\frac{\partial\phi}{\partial\psi}\right)^2\right] = 0$$

and the radial pressure balance equation for the poloidal magnetic flux ψ

$$\Delta^* \psi + 4\pi C_s^2 r^2 \,\partial\rho(\psi, r^2)/\partial\psi = 0$$

These equilibria represent a starting point for MHD stability studies of the reversed field pinch and for the more complicated two-dimensional equilibria in tandem mirror devices.

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SUPERADIABATIC ION MOTION IN THE PRESENCE OF AN ELECTROSTATIC WAVE IN A MIRROR MACHINE*

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ABSTRACT

Rosenbluth[1] and Timofeev[2] showed that a monochromatic, flute mode at the ion-cyclotron frequency causes ions with low perpendicular energy $W_\perp$ to move stochastically, while ions with high $W_\perp$ move superadiabatically. We have improved the model of previous authors[1,2] by including the azimuthal ∇B-drift. Also, we have used the previous method[1] and developed a new, more general method for determining the boundary in velocity space between stochastic and superadiabatic motion. The new method is based on the overlap of the bounce resonances defined by $\omega - kv_D = \overline{\Omega} - 2n\omega_b$, where $\omega - kv_D$ is the wave frequency, Doppler-shifted by the ∇B-drift, ω_b is the frequency of bouncing between mirrors, $\overline{\Omega}$ is the bounce-averaged cyclotron frequency, and n is any integer. Both theoretical methods predict that ions with $W_\perp > W_{\perp S} \approx 8$ keV move superadiabatically; this result agrees with the behavior of calculated ion orbits in a model magnetic field. The value of $W_{\perp S}$ depends only weakly on the axial and radial scale lengths of the magnetic field and on the amplitude Φ of the flute mode ($W_{\perp S} \propto \Phi^{0.23}$). Such a low value for $W_{\perp S}$ disagrees with experimental results that, apparently, indicate stochastic motion of ions with $W_\perp = 40$ keV.[3] This discrepancy cannot be resolved, we believe, by including the collisional drag by electrons, nor by replacing the present slab model by a cylindrical one. Inclusion of effects of the quadrupole field may alter the above results significantly, however.

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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] M. N. Rosenbluth, Phys. Rev. Lett. 29, 408 (1972).

[2] A. V. Timofeev, Nucl. Fusion 14, 165 (1974).

[3] W. C. Turner, UCRL-79334, Aug. 1977.

MONTE CARLO CALCULATION OF ELECTRON HEAT FLOW FOR THE TRANSITION FROM COLLISIONAL TO COLLISIONLESS REGIMES*

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ABSTRACT

In the 2XIIB mirror machine, the plasma density is sufficiently high that at moderate electron temperatures, the electron mean-free-path can be on the order of the plasma length. This parameter regime poses a difficulty for calculating the axial electron heat flow because it is the transition regime between collisional and collisionless cases. In order to solve this problem we have developed a Monte Carlo computer code to determine the axial profile of electron temperature. The Monte Carlo calculation is valid for both short and long mean-free-paths.

The particular operation of 2XIIB modeled is that which uses a gas box located at one mirror to produce a source of cold ions for suppressing microinstabilities. The Monte Carlo code is solved by coupling it to the one-dimensional fluid code PHLOW which gives the axial density profile of cold ions for assumed magnetic field and electron temperature profiles. The axial orbits of the Monte Carlo electrons are followed using both the ambipolar potential profile calculated from PHLOW and the assumed magnetic field profile. These electrons are also randomly scattered according to their collision probability.[1] After a sufficient number of steps, the axial temperature profile of the Monte Carlo electrons is calculated and used as new input to the PHLOW code. The PHLOW code is then run to produce another ambipolar potential profile. The whole procedure is iterated until the electron temperature profile does not change. Comparisons with experimental data from 2XIIB will be made.

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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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TOKAMAK EMPIRICAL SCALING LAWS AND THE MULTIREGIME TRAPPED ELECTRON MODES*

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The interpretation and empirical determination of scaling laws for energy confinement are discussed. Special emphasis is given to the difficulty of determining the temperature dependence of energy confinement time from steady-state ohmically-heated discharges. A large collection of documented data is statistically analyzed to determine an ohmic temperature law:

$$\langle T_e \rangle = \Pi = e^{-9.3\pm1.8} \langle n_e \rangle^{-0.10\pm0.06} a^{-1.29\pm0.18} \times R^{0.66\pm0.15} I^{0.88\pm0.09} Z_{eff}^{0.46\pm0.06} .$$

This corresponds to the electron energy confinement time scaling:

$$\tau_{E,e} = e^{-43.8\pm3.5} \langle n_e \rangle^{0.90\pm0.08} a^{0.89\pm0.20} R^{1.63\pm0.31} \times Z_{eff}^{0.23\pm0.11} (\langle T_e \rangle/\Pi)^{\gamma} .$$

The density averaged temperature is in keV, the volume-averaged density $\langle n_e \rangle$, minor radius a, major radius R, and current I are in mks units; γ is undetermined but probably bounded between ±1 from supplementary evidence to be discussed. No significant magnetic field dependence was found.

We have reexamined the multiregime trapped electron mode theory in comparison with these scaling laws. We have numerically evaluated published estimates of the growth rates. Combined with quasilinear estimates for the diffusivity and several wave amplitude saturation models we have attempted to derive a confinement time scaling for these modes. While the density dependence is in qualitative agreement as noted by previous workers, the strong magnetic field dependence and temperature dependence are not in agreement with empirical formulas.

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THE LOCALIZED INTERCHANGE AND INTERNAL BALLOONING MODE STABILITY*

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ABSTRACT

A set of D-shaped tokamak equilibria has been examined for marginal stability with respect to the localized interchange[1] and internal ballooning[2] modes. These equilibria are obtained numerically but all have the same height to width ratio and cross-sectional area. The critical beta for internal ballooning modes, β_c, is obtained as a function of the safety factor on axis, q_0, from the BLOON[2,3] code with and without the appropriate modification for radial extension[4]. From the localized interchange analysis of equilibria with different values of poloidal beta, we find that $\beta_c(q_0)$ has a maximum. We further find that this maximum lies on the $\beta_c(q_0)$-curve obtained from BLOON. That is, the maximum critical beta for given current density profile, β_c, is given by the Mercier criterion alone.

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Numerical Investigation of the Two Dimensional Fokker Planck and Quasilinear Equations

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Abstract

We investigate the stability of the collisional electron distribution against the high frequency electrostatic modes by solving the Fokker-Planck equation and follow the associated quasilinear evolution of the wave spectrum and distribution function by solving the Fokker-Planck quasilinear equations simultaneously. An implicit collocation scheme using a tensor product of Hermite cubic splines is used to solve the 2D Fokker-Planck equation in the presence of an electric field. Presently, we restrict ourselves to the collision operator which is accurate for the high velocity region ($v \gtrsim v_e$). The runaway production rates are computed and are compared with the published results. The stability of the resulting distributions against high frequency electrostatic modes is also monitored. From an initial marginally stable distribution function the coupled quasilinear equations of the wave spectrum $I(k_\parallel, k_\perp, t)$ and the particle distribution function $f(v_\parallel, v_\perp, t)$ are solved using a finite difference method. The nonlinear development of the instabilities from the anomalous ($\ell = -1$) cyclotron resonance, the creation of the positive slopes, and the plateau formation at the $\ell = 0$ resonance are investigated.

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Numerical Methods for Electromagnetic Instabilities

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Abstract

The cubic spline code,[1,2] developed to find the 2-D structure of trapped electron modes in a torus, has been adapted to the coupled equations for $A_{\parallel}$ and φ in slab geometry. A generalized WKB formalism has been developed and is used to deal with boundary conditions, to which particular attention is paid. Solutions are presented which describe finite beta drift waves,[3] tearing modes,[4] twisting modes,[5] and finite beta effects on localized trapped particle modes.[6] This method is complementary to the variational approach:[7,8] it requires input from known solutions as a starting point but is capable of dealing with more general cases.

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FOKKER-PLANCK STUDIES OF PLASMA HEATING AND CURRENT GENERATION DUE TO RF INDUCED QUASILINEAR DIFFUSION*

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The prospects for heating plasma and sustaining a toroidal current by an RF induced quasilinear plateau in the tail of the electron velocity distribution have been examined analytically by Fisch and Bers [1]. We study the turn-on of the RF induced current using a 2-D Fokker-Planck code [2] with an added quasilinear diffusion operator. In a case in which the turn-on time, i.e., the time for establishment of a raised plateau [1], is much less than the heating time, we obtain approximate agreement with analytic theory as to the power absorption. However, the induced current, which attains a value consistent with [1] after a turn-on time, continues to increase linearly in time. After twenty turn-on periods this effect has not saturated. We also study the effects of an applied electric field and an energy loss term on the power absorption and current production.

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FOKKER-PLANCK/TRANSPORT STUDIES OF THE PDX, PLT AND TFTR INCORPORATING A SELF-CONSISTENT NEUTRALS TREATMENT*

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In contemporary beam-driven tokamaks such as the PDX, PLT and TFTR the injected beam power dominates all other sources of energy input. For regimes in which the energetic ion population comprises a large fraction of the plasma density, the time evolution of the hot ion velocity-space distribution functions must be calculated using the complete nonlinear Fokker-Planck operator. It is equally important to calculate the deposition profile of injected neutrals and to model accurately the transport of neutrals in the plasma.

Toward this end, our Fokker-Planck/transport code [1] has been integrated with self-consistent Monte Carlo beam deposition and neutral transport codes [2,3]. These latter two packages have been generalized to treat an arbitrary number of neutral species.

Investigations into the PDX, PLT and TFTR are carried out. For the PDX the effect of the divertor is studied by varying the recycling coefficient. It is seen that for reference machine parameters (8 MW, 60 keV, 20% recycling, $Z_{eff} = 1.7$) a fusion production rate of 1×10^{16} neutrons/sec is achieved, with 96% of the fusion energy due to reactions involving the energetic ions. For the PLT, the fusion production rate and ion energy are compared with the experimental results, and predictions are made for the forthcoming 3 MW experiment. For the TFTR we consider up to 40 MW of 120 keV D^o beams and investigate the conditions under which Q values of up to 2 can be obtained.

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Buildup of Alpha-Particle Impurities in a Fusing Toroidal Plasma*

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The effect of the spatial thermalization profile on the time evolution and buildup of alpha-particle impurities in a fusing toroidal plasma is under study. Deposited in the plasma interior, the alphas are not effectively controlled by a divertor. Consequently, the buildup of alpha impurities near the plasma center can limit the burn time for future tokamak reactors.

Prior studies of alpha diffusion have generally ignored the details of the thermalization profile, often assuming "in-situ" deposition according to the fusion density. It has been shown, however, that deviations from this assumption can markedly affect alpha diffusion currents during buildup(1) as well as the equilibrium distribution.(2) Such considerations are important since the large orbits and drifts associated with MeV alphas lead to losses during thermalization (loss fraction) and a general flattening of the source profile. Techniques recently developed(3) to study the thermalization process have now made a self-consistent treatment of these effects possible.

Present studies utilize an explicit forward time-differencing diffusion code with fixed spacial mesh and variable timestep. The thermal alpha density profile evolves in the presence of a fuel-ion background with fixed density and temperature profiles. Neoclassical diffusion in a TFTR-size plasma (at 8 keV) with zero alpha reflux from the first wall leads to alpha centerline densities $\gtrsim 1.5\times10^{12}\,\mathrm{cm}^{-3}$ after about 2 min. We find that a realistic thermalization profile leads to centerline concentrations $\gtrsim$17% lower than "in-situ" deposition. More importantly, the buildup rate is decreased by a factor as large as 1.5 for short times. While the loss fraction accounts for some of this temporal effect, the dominant factor is the source flattening. The reduced centerline buildup rate and the presence of higher alpha edge densities during buildup may alleviate impurity control problems.

*This work was supported by U. S. DOE under Contract No. EY-76-S-02-2218.

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Constants of Motions and Higher Order Resonances, Bernard Rosen, Stevens Institute of Technology.

Consider the case where the perturbing Hamiltonian can be written as a multiply-periodic series. If one assumes that a constant of motion can also be developed as a multiply periodic series then the Liouville equation takes the form of an infinite matrix equation.

Taking the Smith-Kaufman model[1] as an example we have obtained a formal solution of the matrix equation in terms of a continued "fraction" of known matrices. This solution suggests that the constant of motion calculated this way is finite at higher order resonances. Numerical calculations on a severely truncated version of the problem are in agreement with this.

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AXIAL HEATING OF LINEAR MAGNETIC FUSION SYSTEMS

by

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The heating of linear magnetic fusion systems by collisional damping of strong axial magneto acoustic waves has been studied with a numerical model which includes radial and axial MHD, physical viscosity, and separate electron and ion temperatures and thermal conduction. Increases of plasma temperature by about a factor of 1.5 to 2.0 are seen on each cycle of the low frequency external magnetic pumping field which produces the axial waves. Parameter studies of heating rate as a function of axial wavelength and frequency of the pump field will be shown. It is shown that this heating method could be an effective and economical alternative to radial shock heating in linear magnetic fusion reactor systems.

Lower Hybrid Wave Propagation in a Turbulent Plasma*

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Recent experimental measurements[1] on the ALCATOR-A tokamak plasma have established the existence of low frequency density fluctuations with amplitudes $\delta n/n$ ranging from 0.1 to 1. The large amplitude fluctuations occur for high density discharges (average density $\bar{n} > 1\times10^{14}$) and are found to be peaked near the plasma edge. They can therefore significantly affect externally launched lower hybrid waves propagating through this region. We obtain a propagation equation which is a linear differential equation with stochastic operators describing the coupling of such steady state electrostatic lower hybrid waves with the background random density fluctuations. Taking an ensemble average and using an operator expansion technique developed by Keller[2] results in an equation for the average wave amplitude. Retaining terms up to second order in the fluctuation amplitudes and Fourier transforming we find a modified dispersion relation for the lower hybrid waves. We analytically solve the dispersion relation for a Gaussian spectral distribution of the fluctuations, to find the damping rate. In the interesting regime of $k_{0\perp}L > 1$, where $k_{0\perp}$ is the perpendicular wavenumber of the lower hybrid wave and L is the correlation length of the turbulence in the perpendicular direction, attenuation can be significant even for moderate levels of fluctuations.

* Work supported by National Science Foundation (Grant ENG 77-00340) and U.S. Department of Energy (Grant EG 77-G-01-4107).

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Fast Liner Scaling*

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Two separate idealizations of plasma heating and fusion effected by a cylindrical liner have been examined. Both rely on the impulse-momentum approximation for treating liner compressibility, first introduced by Shearer and Condit and later extended by Gerwin and Malone to correctly treat cylindrical convergence. This approximation is useful for rapid numerical scans of parameter space.

The first idealization is that the undriven liner possesses initial kinetic energy, and that the wall-contained plasma suffers classical heat conduction across an embedded magnetic field B_θ, and Bremsstrahlung radiation loss. Both a liner experiment and a fast liner reactor are modeled with a 1-D implicit Lagrangian code. Axial thermal conduction loss is included via an analytic approximation. An insulating B_θ field was found to be essential to reduce the heat loss from the high-β plasma for liner velocities of interest. A dense, low-temperature, high-field plasma layer is formed by radial convection to the wall, and central properties are rather uniform. Some aspects of loss-less plasma, undriven-liner scaling found by Gerwin and Malone are retained when the above losses are incorporated.

The second idealization is that the liner is imploded with Z-pinch drive with circuit losses and that the plasma is heated adiabatically. Here, the appropriate nondimensional parameters governing the circuit-liner-plasma dynamics have been identified, and their separate effects have been uncovered by a fast, accurate computer code. Moreover, their effects on the DT fusion gain have been investigated, as well as the effects of two other parameters needed to specify the gain. These numerical calculations have been supplemented by analytical results. Several possible methods of scaling up the device will be presented.

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

The Effect of Convection on the Stability of the Plane Magnetized Plasma Slab

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An MHD boundary layer analysis is performed treating the effect of the convective term of the equation of motion near the singular surface. The nonlinear equations in this region are separable; the time evolution of the solution is determined by the Riccati equation and nonlinear harmonics are generated at wavenumbers which are multiples of the fundamental. This solution is matched to the linear solution in the outer region yielding modes reminiscent of resistive instabilities which nevertheless are not normal modes of the system.

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

Finite-Larmor-Radius Stabilization of m=1 Kink Modes in a Screw Pinch*

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In a recent article, Pearlstein and Freidberg[1] derived a set of macroscopic equations governing perturbations of arbitrary near theta-pinch equilibria from the Vlasov-fluid model; this derivation retained the lowest order effects of finite ion gyro radii. Here, we utilize these FLR equations and write down a dispersion differential equation governing perturbations of a cylindrical high-β screw pinch. The dispersion differential equation reduces to the one derived from ideal magnetohydrodynamics when the ratio of ion gyro radius to pinch radius vanishes. Numerical solutions of the dispersion equation illustrating the dependence of kink mode stability on various parameters (ratio of gyro radius to pinch radius, r_L/a; ratio of wall radius to pinch radius, b/a; plasma β; mode numbers m and k) are presented. We show that a combination of finite gyro radius and wall effects can effectively stabilize all weak magnetohydrodynamic instabilities in a cylindrical screw pinch, including the m=1 mode.

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A Numerical Model for Electron Dynamics in Tokamaks

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A numerical model is being developed to simulate electron dynamics in tokamak discharges. It solves the drift kinetic equation including trapped and untrapped electrons, electric field effects, and Lorentz collisions between electrons and ions. It will be used to study the x-ray spectrum of an Ohmically heated discharge and the spatial dynamics of radio-frequency heating and diagnostic experiments.

This model uses electron energy and magnetic moment as coordinates. The drift-kinetic equation is integrated over particle orbits to obtain a convection-plus-diffusion equation which is solved simultaneously for the bounce-averaged trapped and untrapped electron distribution. This offers an improvement over previous studies of tokamak Ohmic heating,[1] in its inclusions of trapped electrons.

Given these bounce-averaged distributions, the linearized drift-kinetic equation can be solved for the electron response to a perturbation, such as an RF heating pulse. This allows analysis of multi-dimensional problems which are inaccessible to previous models.[2] The structure of this model, and its applications will be presented and illustrated.

Work supported by Department of Energy Contract E(49-20)-1006.

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Modeling of a Reversed-Field Configuration with a 1D Quasiequilibrium Code

by

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A 1D radial code called QUEST, for Quasiequilibrium Stability and Transport, has been developed to study the diffusion of plasma, heat and magnetic flux in reversed-field (belt and theta-pinch) configurations. The code maintains quasiequilibrium ($\nabla p = J \times B$) and can model compression by a moving wall, as well as classical and anomalous (enhanced) cross-field transport. The code has been run (without compression) using initial conditions corresponding to those observed by Hammer, et al. in the SEEBIE experiment.[1] Good agreement with measured magnetic flux and B_θ traces is obtained using purely classical transport coefficients, provided Ohmic heating and axial electron thermal conduction are included in the model.

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CYLINDRICAL, AXIALLY SYMMETRIC MHD TURBULENCE*

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Incompressible MHD turbulence is treated in the presence of cylindrical boundaries. The model treated is non-dissipative and axially symmetric. A spectral expansion is performed for the fields but with different eigenfunction bases depending on whether (I) B_Z is constrained to be constant[1] <u>or</u> (II) B_Z is unconstrained. The absolute equilibrium expectation values of the spectral coefficients can be determined from the Gibbs ensemble appropriate with the constraints imposed by the rugged invariants as well as by any physically imposed constraints.

For (I), it is found that there is a unique state (i.e., a unique B_θ profile) for which large velocity fluctuations are not expected. All other states are unstable. The stable state exists for arbitrary toroidal current.[1] For (II) and for sufficiently low values of the toroidal current there is a unique stable state which corresponds to the force-free Taylor state.[2] As the toroidal current increases one obtains (stable) B_Z reversal. If the toroidal current is increased further then one obtains magnetic islands and all states are now unstable.

These results are in striking contrast to both a linear δW analysis and to a linearized treatment of the spectral coefficients. Both these linearized theories predict stability for all $k = 0$ modes for arbitrary B_θ profiles.

*Work supported in part by D.O.E. Grant EY-76-S-05-5260

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Effect of Diamagnetic Currents on Drift Waves in Toroidal Geometry*

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We consider the effect of toroidal diamagnetic currents on the frequency and stability of drift waves in toroidal geometry. A differential equation for the radial mode structure is derived in the weak coupling limit. It is found, for small poloidal mode numbers, that the toroidal currents can be more important than the polarization currents. The bearing of the solutions of the eigenmode equation on the stability of the drift wave will be discussed.

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Two-Dimensional Structure of the Trapped-Ion Instability *

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We present some preliminary results of a calculation of the two-dimensional structure of the trapped-ion instability. Our approach is based on a poloidal and toroidal Fourier decomposition of the perturbed electrostatic potential and a truncated Taylor series for each Fourier coefficient in the radial variable. The resulting dispersion relation is a set of coupled ordinary differential equations which is solved numerically by the method of finite elements. Our analysis is limited to plasmas having few mode-rational surfaces ($\lesssim 10$) and to instabilities satisfying $k_r \rho_{bi} < 1$. Here k_r is the radial wave number of the mode and ρ_{bi} is the trapped-ion banana width. The results presented range from $k_r \rho_{bi} \ll 1$ up to $k_r \rho_{bi} \lesssim 1$, where our approach breaks down. The full two-dimensional calculation of the instability allows us to look at the effects of shear, circulating particle resonances, and temperature and density profiles over the plasma cross section.

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Rotating Magnetic Islands*

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Taking into account the Hall term in Ohm's law gives rise to a rotating island structure similar to that seen experimentally in Tokamaks using x-ray measurement.[1] Following the nonlinear evolution of these rotating islands numerically indicates that the saturation mechanism is independent of the hall term. Indeed we can show this to be true and present analytic results that show that the saturation model previously presented[2] is still applicable. This argument can easily be extended to include viscous forces as well.

The above discussion is applicable to modes with poloidal mode number of 2 or greater. The situation is entirely different for M = 1 modes. Here the modes continue to grow on a tearing mode time scale until the island structure is completely destroyed. By using a model in which finite larmor radius effects only reduce the growth rate of the m = 1, Waddell et al.,[3] have obtained very good agreement with experimental results from Ormak on the internal saw tooth. We are now in a position to test this model and the results of this test will be presented.

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* Work supported by U.S. DoE Contracts EY-76-C-02-3073 and EY-76-S-02-3237.

Alfvén Heating Via Magnetosonic Modes in Large Tokamaks *

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Tokamaks of the PLT size are the first to nominally permit propagation of magnetosonic modes at frequencies that are a modest fraction of the ion-cyclotron frequency. (Typically $\omega/\Omega_i \approx 0.5$). In this regime, the equation governing magnetosonic modes contains a closely spaced triplet of cutoff-resonance-cutoff surfaces which arises from the finite value of ω/Ω_i and is not found in MHD Treatments.[1] In addition there is another singularity in the equation which coincides with the resonance surface and which gives rise to the Alfven heating of MHD theory. We calculate the dissipation resulting from these effects and determine the Q of toroidal eigenmodes.

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* Work supported by U. S. DoE Contract EY-76-C-02-3073.

A Coronal Atomic Physics Algorithm For Low and High Z Impurities*

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An algorithm for the computation of atomic physics rates for ions of arbitrary Z (Z less than 99) has been constructed for coronal conditions. The general prescriptions are similar to those used in Post, et al. [1], but the average ion model has not been used. The rates are given in terms of individual ionic species. The rates are thus suitable for inclusion in a generalized impurity transport code, especially since the prescriptions are valid for any Z (less than 99).

Radiation rates and the fraction of each ionic species present at a given temperature(in coronal equilibrium) have been computed and compared with previous work. The agreement is very close with the average ion model results. The results for tungsten show slightly larger values for the radiation and a somewhat different temperature dependence than the average ion model results, especially near closed shells. This is primarily due to the inclusion of transitions from inner shells for dielectronic recombination, which were not included in the older results[1].

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SIMULATION OF 2XIIB EXPERIMENTS WITH A GUIDING CENTER CODE*

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ABSTRACT

Recent 2XIIB experiments have included three types of neutral-beam injection: (1) tangential with ions displaced inward from the point of deposition and leading to high β values; (2) tangential with ions displaced outward leading to a flat or hollow density profile at lower β; (3) head-on injection giving a nearly flat density profile. We have used a code which computes the evolution of the density of guiding centers† to simulate these experiments. The code includes displacement of the trapped ions, multiple generation charge-exchange off injected beams, surface erosion by reflux atoms and molecules, but, at present, does not include energy equations. In using the code to simulate the experiments, we consider the particle confinement time ($n\tau_p$) as a parameter to be adjusted to fit the observed steady-state central line density. The behavior of the streaming target plasma is modeled to reproduce the initial plasma build-up rate. Resultant values for $n\tau_p$ are in the range 5 - 7 X 10^{10}cm^{-3}-s. Best agreement between computed and experimental line density profiles occurs for case (1) above. For cases (2) and (3) the profiles are somewhat broader than those measured. The simulation also yielded somewhat more of a dip in the central density for case (2) than was observed. Possible explanations for less dip include inward fluting, since such a profile is MHD unstable, diffusion in the ever present rf, or increased penetration of streaming plasma because of the lower electrostatic potential.

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STABILITY OF HIGH-m TEARING MODES*

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Magnetic perturbations arising from high-m (m = poloidal mode number) tearing modes may be responsible for the anomalous electron energy transport in present tokamaks. Thus it is useful to determine the range of collisionality for which such modes can be unstable. Previous work[1] has shown that tearing modes with large values of m are stable if $\nu_c/\omega_* \ll 1$, where ν_c is the electron-ion collision frequency and ω_* is a typical diamagnetic drift frequency. In collisionless plasmas the dominant free-energy source is the magnetic field energy. Hence high-m modes, which greatly distort the field lines, are necessarily stable. In the opposite limit, $\nu_c/\omega_* \gg 1$, the temperature gradient provides an additional source of free energy which can destabilize high-m drift-tearing modes and lead to enhanced thermal conductivity.

The present calculation extends the linear theory of Ref. 1 to allow arbitrary collisionality by making use of a velocity-dependent Williamson collision operator.[2] This enables us to study the onset of instability for high-m, ∇T-driven tearing modes with increasing collisionality. Numerical results will be given for typical tokamak parameters.

*Work supported by USDOE and NSF.

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Stability of Axisymmetric Field-Reversed Equilibria of Arbitrary Ion Gyro-Radius*

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An alternative derivation of the "energy principle" for axisymmetric field reversed equilibria obtained previously[1] by varying the total system energy, angular momentum and entropy has now been obtained directly from the dynamical equations. Particles that carry the azimuthal current are described in the Vlasov formalism allowing for arbitrary gyro-radius while the background plasma is approximated by two-fluid equations. The "energy principle" is developed in two limits: (a) $n_i >> n_b$ and (b) $n_i << n_b$, where n_i and n_b are the background ion and the ring ion densities respectively. Two special cases viz. a long, thin P-layer and thin, bicycle tire shaped ion ring are examined in detail.

*Work supported by U.S. Department of Energy Contract #EY-76-S-02-3170.

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STRONGLY INHOMOGENEOUS VLASOV SLAB EQUILIBRIA*

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ABSTRACT

We describe a method for constructing exact Vlasov slab equilibria to model high-density plasmas having scale lengths for density variation and magnetic shear that are comparable with typical ion gyroradii. To demonstrate the method, we present numerically calculated equilibria modeling the sheath region outside a Tormac plasma.

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CROSS-FIELD TRANSPORT OF A HIGH-β PLASMA

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Approximate current sheath broadening rates in a nearly sharp-boundary plasma column are obtained by analyzing the cross-field plasma transport in a slab geometry. We assume classical transport of a quasi-static plasma with unshorted electric fields and uniform temperature. This description allows a self-similar model of plasma behavior in which the independent variables, a magnetic flux coordinate and a stretched time coordinate, are incorporated in a single similarity variable. Assuming a vacuum boundary ($B \to 0$ outside the plasma), the resulting ordinary differential equation has a one-parameter family of solutions, the parameter being the value of β in the plasma interior. The present model also admits a reversed-field configuration and therefore can be used to describe the cross-field transport in reversed-field linear plasmas. We derive the plasma equations and present results from computer calculations.

Sheath broadening and the leakage of flux into a high-β plasma column are shown to have a strong effect on plasma endloss for free-streaming, and cusped-end linear plasmas. For field-reversal, cross-field transport is shown to dominate plasma endloss scaling due to leakage of plasma from closed to open field lines.

Finally, the effect of anomalous transport on the present solution is described. Because of finite-β stabilization, the lower hybrid drift (LHD) instability is restricted to the lower density regions of the current sheath. The importance of LHD in increasing cross-field transport and linear plasma endloss is estimated.

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NONLOCAL THEORY OF DRIFT WAVES*

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Our ealier study[1] of drift waves in shearless plasma sheaths having density gradient length, L, comparable to the ion cyclotron radius r_{ci} used a differential equation approximation to the integral-differential equation satisfied by the electrostatic potential. We have now examined the properties of the full equation, taking advantage of the fact that the integral operator involved has Hermite polynomials as eigenfunctions in the small frequency ($\omega << \omega_{ci}$) and small transverse wavenumber ($k_\perp r_{ci} << 1$) regime. Expansion in Hermite polynomials and truncation of the resulting infinite set of equations yields the eigenfunctions and associated growth rates of the ion acoustic type modes as functions of $(k_y/k_z)\ (m_e/m_i)^{\frac{1}{2}}$.

*Work supported by NSF and USDOE.

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PHYSICAL PROPERTIES OF "DISCONNECTED" BALLOONING MODES*

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Ideal MHD, "disconnected" ballooning modes can be driven unstable by the locally unfavorable magnetic curvature, in finite β confinement configurations, over consecutive segments of a given field line as if these were independent of each other. Their topology is determined by minimizing the associated variation of magnetic energy and the influence of shear. We have evaluated the properties of the marginal stability condition $\beta = \beta_c$ where $\beta_c \sim G r_p R_o (2\pi/L)^2$, $r_p = -(d\ln p/dr)^{-1}$, L is the periodicity distance of the poloidal magnetic field along a given line of force, R_o the radius of magnetic curvature and G a finite function of magnetic shear. Our analysis takes into account that, as β becomes finite, (1) L tends to become shorter than $2\pi q R_o$ (q is the rationalized inverse rotational transform), (2) r_p decreases and (3) the magnetic shear parameter becomes a function of the poloidal angle.

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STABILIZATION OF THE "RECONNECTING" AND TEARING MODES IN THE COLLISIONLESS REGIME *

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Current carrying toroidal plasma columns are observed to be affected by $m^o = 1$ and 2 internal "reconnecting" and "tearing" modes which depend on electrical resistivity to produce reconnection of magnetic field lines. A two-fluid analysis[1] and recent Alcator experiments suggest that the modes are suppressed when the reconnection layers are brought to a relatively high electron temperature. In fact, our studies of the collisionless Vlasov theory solutions for these modes show that ion Landau damping exerts a strong stabilizing influence. This previously[2] neglected effect and that of finite ion gyro-radius are significant factors in a fourth order differential equation which allows proper matching of solutions across the reconnection layer. The resulting instability is considerably milder than in regimes dominated by collisional resistivity.

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* Supported in part by Department of Energy.

NONLINEAR PROPAGATION OF ION CYCLOTRON WAVES IN A HOMOGENEOUS PLASMA*

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Large amplitude ion cyclotron waves in a homogeneous plasma are studied in the electrostatic approximation. The nonlinear mechanism considered is the frequency shift of the ion gyrofrequency due to the presence of the electrostatic wave. This nonlinear frequency shift was previously applied to the case of the drift-cyclotron instability in an inhomogeneous plasma and was seen to lead to a detuning of the resonance.[1] In the present, homogeneous case, we do not consider an instability, but examine the space-time evolution of wave packets. The frequency shift, which for large $k\rho_i$ is proportional to the ponderomotive potential $\psi = e^2k^2|\phi|^2/M(\omega-n\Omega)^2$ is seen to importantly affect the nonlinear behavior. Equations describing the evolution of the envelope are derived in various regimes of interest. In particular, it is shown that the nonlinear Schrödinger equation results. Solitons and soliton collapse phenomena are discussed with application to magnetic confinement devices and the magnetosphere.

*Work supported by DOE and National Research Council of Canada.

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THE EFFECTS OF ION NONLINEARITY ON THE PARAMETRIC DECAY OF LOWER HYBRID WAVES OF FINITE PROPAGATION VECTOR IN A PLASMA*

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A theory is developed to include both electron and ion nonlinear response to the parametric decay of lower hybrid waves of finite wavenumber in a plasma. Previously, the drift kinetic equation was solved to include the effects of electrons on the nonlinear coefficients of the parametric decay and quasimode excitation by a lower hybrid wave with components of the propagation vector both perpendicular and parallel to the external magnetic field.[1] In this work, a method is developed to calculate the ion nonlinear effects by writing the Vlasov equation in terms of the guiding center coordinates as canonical variables. The purpose of the work is to evaluate the contribution of ions to the coupling coefficients for parametric decay, quasimode decay, oscillating two-stream instability, and modulational instability of a lower hybrid pump. In addition, we investigate the nature of the hitherto less explored three-wave decays into (i) ion cyclotron and lower hybrid waves when the growth rate is comparable to $\omega-\omega_{ci}$ or even larger, and (ii) ion Bernstein and lower hybrid waves when $\omega \lesssim \omega_{ci}$ or $\omega \sim n\omega_{ci}$. We find that the contribution of ions is important only for the decay into a Bernstein wave of short perpendicular wavelength ($\omega >> k_z v_e$, $k_\perp \rho_i >> 1$). By examining the various channels of decay, we find that the oscillating two-stream instability and nonlinear Landau damping by electrons are the dominant channels in the high density region. Modulational instability and the decay into an ion acoustic wave are irrelevant to tokamak heating.

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Impurity-Driven Drift Eigenmodes in a Sheared Magnetic Field*

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It has been emphasized in recent calculations that universal[1] and dissipative[2] drift eigenmodes are actually stable in a slab geometry with magnetic shear. This contradiction of earlier work resulted from taking into account the proper non-resonant electron response (i.e., the complete Z function contribution, with Z being the plasma dispersion function). In the present paper the familiar impurity-driven drift instability, derived by Coppi, et al.[3] in the radially local limit, is examined within this same framework. Specifically, we retain the complete Z-function response of the hydrogen ions, which drive these instabilities and have a role analogous to that of the electrons for ordinary drift modes. The resultant second order radial differential equation has been solved employing a WKB procedure[4] and also by means of a finite difference ("shooting") code. It is found that unstable impurity-driven drift eigenmodes can appear over a wide range of parameters, and that the basic qualitative features of these instabilities from the local calculation can be recovered. Comparison of results from the WKB and shooting code calculations yield very good agreement. The sensitivity of these eigenmodes to magnetic shear strength, impurity concentration, equilibrium profiles, etc. will be discussed.

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The Effects of Viscosity on Classical Diffusion Near an X-Point*

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In the absence of viscosity, classical diffusion in the presence of an x-point is singular in two respects: a) all the diffusive flow from inside the separatrix to outside passes through the x-point; b) the flow velocity along the magnetic surface is infinite along the separatrix. By introducing a model viscous force $\nu\nabla^2\vec{V}$ into the two fluid momentum equations, we demonstrate the existence of a boundary layer near the separatrix in which viscous effects dominate the transport and smooth out these singularities. The width of this boundary layer scales as $\nu^{1/3}$. We now find: a) most of the flow crosses the separatrix near the x-point; b) the flow velocity along the surface is now finite and scales as $1/\nu$ near the separatrix.

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MHD/TRANSPORT EFFECTS ON TOKAMAK CONFINEMENT SCALING*

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Mirnov has recently shown that low m-number (2 or 3) MHD oscillations play a decisive role at the highest current in tokamaks. This situation may serve as a model for the onset of other MHD instabilities (say ballooning) which are expected when intense heating experiments probe new regimes.

The semi-analytic model proposed by Carreras, Waddell, and Hicks (this meeting) which has successfully compared with their 3-D numerical simulations of the resistive tearing instability, has been coupled to the Oak Ridge Tokamak Transport Code. While cross-island transport rates are uncertain, the effects of large scale saturated islands on confinement scaling have been estimated, and found to correspond to the universal curve of τ_E vs q(a) presented by Mirnov. The beneficial effects of additional heating inside the singular surface (whether ohmic, ECH, or neutral beam) have been reproduced as well. Further studies of transport rates near and within the island region are needed for the modes considered: m = 2 through 5, n = 1 and 2.

Intense neutral beam heating experiments should present a situation similar to that observed at high current in present tokamaks: a new class of MHD instabilities (ballooning) is expected to occur as pressure gradients exceed acceptable bounds. A limitation on gradients does not present a simple a priori limit on β. Thus, we have examined the onset of anomalous transport with the axisymmetric (2-D) transport code, using criteria developed by Dobrott et al., and by Rutherford et al. to model the onset of enhanced transport. Beta values larger than those cited from linear stability theory may be expected, provided that the violation of linear theory does not lead to immediate disruption.

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DENSITY FLATTENING AND QUASILINEAR EVOLUTION OF INDIVIDUAL MICROMAGNETIC CELLS*

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ABSTRACT

A number of collective phenomena have been identified which can destroy magnetic surfaces in tokamaks through creation of fine-scale magnetic islands. Due to micromagnetic island formation, the pressure gradient tends to diminish along the reconnected field line on a fast or MHD time scale. From a linear profile, the pressure evolving according to $\vec{B} \cdot \vec{\nabla} p = 0$ ($\vec{B}$, the total magnetic field) is not analytic around the separatrix where the island rotational transform is practically null. A boundary layer, allowing an irreversible process, permits the quasilinear evolution of the instability to be calculated. Results and possible applications to a macro-island will be discussed.

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THE ROLE OF EQUILIBRIA IN NONCIRCULAR TRANSPORT CALCULATIONS

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A transport code for tokamaks with non-circular flux surfaces is under development at the National M.F.E. Computer Center. Two questions concerning the formulation have arisen: What are the effects of anisotropic pressure on the equilibrium, and in what manner should the magnetic fields be advanced in time?

The first question has not been addressed in past transport code formulations; these calculations have assumed scalar plasma pressure, which is a function of only the poloidal magnetic flux coordinate ψ. However, in tokamak devices where energetic neutral beams supply a significant fraction of the energy input, the plasma pressure may become anisotropic due to the directed nature of the beams. To study the effects of anisotropy, we compute equilibria using model tensor pressures of the form $\underline{\underline{P}} = P_{\perp} \underline{\underline{I}} + \left(\frac{P_{\parallel} - P_{\perp}}{B^2}\right) \underline{B}\,\underline{B}$ where $\underline{B}$ is the magnetic field and the pressure components $P_{\perp}$ and $P_{\parallel}$ depend on both ψ and $|\underline{B}|$. Diamagnetic and paramagnetic responses of the plasma to the vacuum toroidal field are also examined. The maximum attainable beta is limited by the requirements that reversed-current regions be avoided, the safety factor be greater than unity, and mirror and firehose modes be stable.

Other transport code difficulties relate to whether or not the equilibrium condition $0 = -\nabla \cdot \underline{\underline{P}} + \frac{1}{c} \underline{J} \times \underline{B}$ should be ignored while the poloidal and/or toroidal magnetic field components are advanced in time via Faraday's Law $\frac{1}{c} \frac{\partial \underline{B}}{\partial t} + \nabla \times \underline{E} = 0$; the particle and energy fluxes in the plasma are assumed to be given in terms of local or flux surface averaged transport coefficients. We are currently investigating these options with a simple one-dimensional model.

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Fusion Product Heating of Field-Reversed Mirrors*

by

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Recent estimates of fusion product (fp) heating in D-^{3}He field-reversed mirror (FRM) plasmas indicate that near-ignited operation (Q>10) is possible. Using an absolute confinement criterion developed by M. Wang,[1] we find that 88% of the 3.67-MeV alphas and 55% of the 14.1-MeV protons are absolutely confined in a 60-kG FRM with 20-cm plasma radius. This is quite encouraging, however, many particles that are absolutely confined only spend a small fraction of their time in the closed-field region. In order to obtain a more accurate evaluation of the actual energy deposition, a Monte-Carlo particle code (MCFRM) has been written. This code follows particle trajectories during slowing down, and will eventually include pitch angle scattering effects in order to determine the deposition of fusion "ash." Heating profiles from MCFRM for typical FRM parameters will be presented along with a discussion of the sensitivity of the FRM energy multiplication to fp heating.

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CURRENT DRIVEN DRIFT WAVES AND TRAPPED ELECTRON MODES IN SHEARED MAGNETIC FIELD*

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Recently it was shown that the universal instability is suppressed by any amount, however small, of shear in the magnetic field. In this paper we analyze, numerically, the current driven drift wave in a sheared field, in both slab geometry and toroidal geometry. We use full Z-functions and also include the effects of temperature gradients, electron-ion collisions, and trapped electrons. In slab geometry we find that the collisionless current-driven, drift wave remains unstable provided the threshold $u/v_e > L_n/L_s$ is satisfied, a result in agreement with previous analytic results. A negative electron temperature gradient, $\eta \equiv d\ell nT/d\ell nN < 0$, which does not, by itself, produce instability in a sheared field, reduces the current threshold for instability and enhances the growth of the instability. A positive temperature gradient, $\eta > 0$, does not readily stabilize the current-driven drift wave as is the case in an unsheared field, but merely increases the current threshold, even for $\eta = +1$. Interestingly, the growth rate for the current-driven instabilities maximizes for long-wavelength modes $k\rho_i \ll 1$, which are effective in producing radial diffusion. The radial extent of these modes is also quite broad. Electron-ion collisions reduce the growth rate of short wavelength spectrum of the current-driven drift mode, while enhancing the growth rate for the long-wavelength spectrum. In toroidal geometry trapped electron modes are found to be unstable when the Z-functions for the free-streaming electrons are introduced. Also, we report on the combined effects of current and trapped electrons on drift wave stability.

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FINITE BETA EFFECTS ON THE ION-CYCLOTRON-DRIFT INSTABILITY*

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The ion-cyclotron-drift instability, resulting from coupling of an ion drift wave to ion cyclotron waves, may lead to anomalous transport in plasmas with moderate inhomogeneities $[r_{Li}/L_N \gtrsim (m_e/m_i)^{1/2}]$. This instability can be present in late time post-implosion theta pinches and may be relevant to the straight section of the Tandem Mirror Experiment (TMX), the first high density solenoidal plasma with a millisecond lifetime. We present a detailed analysis of the effects of finite plasma beta $[\beta=8\pi M(T_i+T_e)/B^2]$ on this instability. The analysis is based on numerical solutions of a fully electromagnetic kinetic dispersion equation which treats the magnetic drifts of both electrons and ions. A numerical formulation is chosen which allows for strong ion inhomogeneities and permits the continuous tracking of the instability for arbitrary ω/ω_{ci}.

The ion-cyclotron-drift instability has a real frequency, $\omega_r \gtrsim kV_{di} \cong \ell\omega_{ci}$ and growth rate $\gamma \gtrsim \ell(m_e/m_i)^{1/4}\omega_{ci}$ for an equilibrium inhomogeneity $(r_{Li}/L_N) \approx 2\ell(m_e/m_i)^{1/2}$. Maximum growth occurs for wavenumbers by $kv_i \gtrsim \sqrt{2}\omega_{LH}$ with $\underset{\sim}{k}\cdot\underset{\sim}{B}=0$. For inhomogeneities, $(m_e/m_i)^{1/2} \gtrsim r_{Li}/L_N \lesssim (m_e/m_i)^{1/4}$, the unstable k-spectrum exhibits a complicated banded structure.

Analytic theories predict a reduction of the ion-cyclotron-drift growth rate by ion magnetic drift resonances,[1,2] and complete stabilization of the mode by electron magnetic drift resonances.[2] We find that while both of these effects have a stabilizing influence on the mode, electromagnetic effects prevent actual stabilization. When only the first harmonic is excited the various finite beta effects act to reduce the electrostatic growth rate by 50% for $T_e=0$ and by 90% for $T_e=T_i$ for the value $\beta=1$. When several unstable harmonics are present, finite β skews the spectrum so that the longer wavelength modes are more unstable than their shorter wavelength counterparts.

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A UNIFIED APPROACH TO BALLOONING AND TRAPPED PARTICLE INSTABILITIES

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A unified, electromagnetic dispersion relation for the curvature-drift driven MHD ballooning instabilities and the trapped electron drift instabilities has been derived from the drift-kinetic equation in toroidal geometry.[1] The two branches of the dispersion relation, the shear Alfven (MHD) and the electron drift (trapped electron) are coupled by curvature drift as well as finite ion gyroradius effects. This unified dispersion relation has been used to study kinetic effects on ballooning modes, as well as curvature drift effects on the trapped electron modes.

In the MHD limit, the dispersion relation yields the usual MHD ballooning mode and the critical β, β_{crit}, for stability in a tokamak with circular cross section $\beta_{crit}=L_n/q^2R$ where $L_n=\left|\frac{1}{n}\frac{dn}{dr}\right|^{-1}$, and q is the safety factor and R is the major radius. Finite ion gyroradius effects lead to a real frequency contribution to the eigenvalue $\omega_r = \frac{1}{2}k_\perp V_{di}$ where $k_\perp=m/r$ and V_{di} is the ion diamagnetic drift velocity. Thus different poloidal mode (m) have different eigenvalues and thus the global degenerate modes seen in the MHD analysis are converted to radially localized modes. This may have important consequences in the nonlinear phase. Other kinetic effects analyzed are found to only weakly affect the growth rate and critical β.

The effects of the curvature drift of the untrapped particles on the trapped electron mode has been found to be destabilizing in the absence of an electron temperature gradient. For modes with $\omega_*<<\nu^*$, where ω_* is the electron diamagnetic drift frequency and ν^* is the effective collision frequency for detrapping, and with $(k_\perp\rho_i)^2>>L_n/q^2R$ where ρ_i is the ion gyroradius, the growth rate and eigenmode are, in the absence of an electron temperature gradient

$$\gamma \simeq 4\sqrt{\frac{2\varepsilon}{\pi}}\,\frac{\omega_*^2}{\nu^*}\left\{\left(\frac{(k_\perp\rho_i)^2}{2}+\frac{L_n}{\sqrt{2}R\tau}\right)-k_L c_s^2\,\frac{1}{\tau\omega_*^2}\right\}(1+\tau)$$

$$\phi\simeq 1+\sqrt{2}\cos\theta$$

where $c_s^2=T_e/m_i$, $k_L=1/(qR)$ and $\tau=T_e/T_i$. The $k_\perp\rho_i$ contribution is the usual finite ion gyroradius destabilization and the L_n/R contribution is from the curvature drift. The eigenfunction balloons out in the region of bad curvature.

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THEORY OF NONTHERMAL RADIATION AT ω_{pe} FROM TOKAMAKS*

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Intense electromagnetic radiation near ω_{pe} has been observed in TFR,[1] Alcator,[2] Microtor,[3] and PLT[4] in both high and intermediate density regimes. The power spectrum shows a peak near ω_{pe} of the order of black body level as well as other peaks at cyclotron harmonics. In the present analysis, this emission is interpreted as the collective bremsstrahlung radiation induced by the runaway electrons. Because the runaway distribution is flat and anisotropic, the fluctuation is enhanced over the thermal level due to the reduction of Landau damping and the enhancement of spontaneous emission through the multiple cyclotron resonances. The fluctuation collides with low frequency ion fluctuation to produce radiation in the neighborhood of ω_{pe}. The two polarizations, ordinary and extraordinary, are also distinguished, and show significant modification to the one calculated by Papadopoulos et al.[5] for the unmagnetized case. The time evolution of the radiation is also demonstrated. The intensity decays during the discharge in the case that the runaways are not very well confined. But in the case of extremely good confinement such as PLT the radiation level actually increases in some cases. The detailed spectrum is to be compared with experimental results.

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Rigid-Drift Magnetohydrodynamic Equilibria for Cylindrical Pinches*

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The rigid-drift equations of magnetohydrodynamic equilibria in cylindrical geometry are:

$$(\vec{\nabla} \times \vec{B}) \times \vec{B} = 4\pi\vec{\nabla}p \; ;$$

$$J_z \propto n \; , \; J_\theta \propto rn \; ;$$

$$p \propto n^\Gamma \; ;$$

where $\vec{B}(r)$, $\vec{J}(r)$, $p(r)$, and $n(r)$ are the magnetic field, current density, pressure, and number density, respectively. Such magnetohydrodynamic equilibria have corresponding Vlasov equilibria.

When $\Gamma=1$ (the isothermal case), these equations produce the Bennett profiles for the case of a pure Z-pinch.[1] The case of a pure θ-pinch with $\Gamma=1$ has been solved by Morse and Freidberg.[2] In both Z- and θ-pinch cases with $\Gamma=1$, one has pressure profiles that drop to zero only at $r=\infty$.

We have analytically solved these equations (in terms of an infinite series of hypergeometric functions) for an arbitrarily pitched current density when $\Gamma=2$. This value of Γ implies a local temperature that is proportional to the local number density.

The shapes of the pressure and magnetic field profiles are completely determined by the model once two parameters are specified:

a) the local plasma beta on axis,

b) a quantity related to the pitch of the current density.

These profiles have been plotted with the aid of MACSYMA. We find the possibility of occurrence of hollow profiles and reversed B_z fields, simultaneously or independently. The pressure always falls to zero at a finite value of the radius.

This analysis may have relevance to understanding and manipulating ZT-40 equilibria.

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Simulation of a High Frequency Loss Cone Instability*

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Results of particle simulation of the high frequency (~ lower hybrid) mirror loss cone instability[1] are presented. The simulations were done in the two spatial directions perpendicular to the external magnetic field in a finite beta (ion beta ~ .3), strongly inhomogeneous (density scale length ~ .2 ion Larmor radius) configuration. In this regime the instability is basically fluid-like and resembles the lower hybrid drift instability. Comparisons with linear and nonlinear theory as well as with simulation results for the lower hybrid drift instability[2] will be discussed. Also, measurements of the rate of diffusion of ions into the loss cone and calculations based on quasilinear theory will be presented.

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Electrostatic Heat Flux Instabilities and the Reduction of Axial Thermal Loss*

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If nonclassical effects can reduce axial thermal loss in comparison with the collision-dominated result, the reactor scaling of open confinement devices can be improved. One such possible effect is an anomalous reduction of the axial heat flux $\vec{q}_o$ by instabilities driven by that flux.

To study the effects of a possible heat flux limit, we have solved the one-dimensional electron thermal equation in the linear theta pinch geometry.[1] So far, we have two results: (1) Nonclassical effects are most likely to occur in the low-density end regions, and (2) the (arbitrary) use of a heat flux limit not only increases the thermal loss time but also flattens the axial temperature profile, by comparison with classical results.

To understand how a heat flux limit might arise, we have also studied the various possible electrostatic heat flux instabilities in a homogeneous Vlasov plasma.[2] For a wide variety of conditions, thresholds much below the classical heat flux limit are provided only by the ion acoustic instability, which unfortunately operates only at $T_e >> T_i$. Undaunted, we are pursuing a second-order theory of these instabilities. This work extends conventional quasilinear theory to include electric fields induced by the zero current condition. The important results thus far are: (1) the effect of these heat flux instabilities is always to reduce $\vec{q}_o$, and (2) the effective q-reduction frequency is smaller than the usual anomalous momentum loss rate due to ion acoustic turbulence.

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"MOST PROBABLE" STATES IN MAGNETOHYDRODYNAMICS*

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We consider the most probable states of an MHD fluid which are consistent with certain limited pieces of information imposed by the known global constraints. A measure for the probability of an MHD state must be assumed, and the one we choose is motivated by the "information theory" formulation[1] of statistical mechanics. There, the logarithm of the probability of a continuous function $f(x)$ is defined as $-\int f(x)\ell nf(x)dx$, up to an additive constant. We maximize this measure for the axial magnetic field and electric current field in an axisymmetric linear screw pinch equilibrium, subject to the constraints of given magnetic energy, helicity, axial magnetic flux, and total axial current. The result[2] is a pair of coupled nonlinear differentio-integral equations for the magnetic field and the vector potential which are a natural generalization of the Sinh-Poisson equation previously derived for the electrostatic guiding center plasma.[3] One special case is analytically soluble, but most of these most probable (Grad-Shafranov) equilibria will require numerical solution.

*Work supported in part by NASA and DOE.

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Calculations of Alpha Particle Heating in Tokamaks*

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An algorithm has been constructed to calculate the alpha particle heating of tokamaks. The algorithm is fast (about 15 seconds of PDP-10 KI time), small, and convenient for tokamak transport codes. The effects of finite orbit width, finite Larmor radius, and finite slowing down time are all taken into account; changes in the particle trajectories as they slow down and pitch-angle scatter are not presently included. The birth-points of a number of alphas are distributed in phase-space using an "anti-thetic" Monte Carlo technique. The trajectories are then determined from an algebraic equation derived from the quasi-constants of the motion: the energy, the magnetic moment, and the canonical angular momentum. This avoids the equivalent (and time-consuming) integration of the guiding center differential equations. Concentric, circular flux surfaces are currently assumed but the method can be easily generalized to more realistic equilibrium cross-sections. A one-group modified Fokker-Planck scheme is used to compute the time history of the alpha heating.

It has been found that for a given alpha birth distribution, the parameters which affect the containment most profoundly are the plasma current and the aspect ratio. The current profile has only a small effect on the containment.

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D13

Annihilation Model of the Tormac Sheath*

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In the tormac device, the plasma pressure is held primarily by a thin mirror confined sheath supported by an external poloidal cusp magnetic field. Since the strongest gradients are across the sheath, we average along the sheath to give a one-dimensional slab model. The mirror losses of particles and energy out the cusps can be expressed in terms of averaged plasma parameters and act as annihilation terms in the one-dimensional fluid equations. Although this fluid treatment of the ion dynamics across the sheath is only approximate, it should be sufficient to give the basic features of the plasma profiles.

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Hamilton's Principle for a Hydromagnetic Fluid with a Free Boundary*

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(i) We have generalized Newcomb's[1] nonlinear Lagrangian by the inclusion of a vacuum region. The availability of a nonlinear Lagrangian offers the possibility of investigating mode coupling effects.

(ii) We have found a method of expansion for the Lagrangian which needs only a linearization to treat linear problems and which produces the familiar form of the potential energy δW in a natural manner.

(iii) We have found variational principles for the inductance matrix $L_{k\ell}$ and scalar magnetic potential χ which allows Galerkin's method to be used in the vacuum region.

(iv) We have introduced generalized coordinates to describe the currents flowing in the plasma and external conductors, thus allowing the treatment of external circuits: e.g. the effect of passive feedback on axisymmetric stability.

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Theory of Dissipative Drift Instabilities in Sheared Magnetic Field*

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Using several different non-perturbative techniques, we have investigated the stability of electrostatic drift-wave eigenmodes in a resistive plasma with finite magnetic shear. It is found that in the slab approximation, where usual shear damping is operative, resistivity contributes to an enhancement of this damping and the enhancement factor increases with the electron-ion collision frequency ν_{ei}. Thus, no unstable eigenmodes result. If the shear damping is nullified, either by introducing a strong spatial variation of the density gradient or by working in toroidal geometry with strong toroidal coupling effects, then unstable eigenmodes are recovered and the growth rate increases with ν_{ei}. A perturbation calculation shows that inclusion of finite electron thermal conductivity as well as temperature gradients does not alter these conclusions. Extensive numerical calculations and relation to published experimental results are also presented.

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Resistive Drift and Alfvén Instabilities in Sheared Magnetic Fields *

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It is shown that, due to finite-β effects, there exists unstable resistive drift and Alfvén eigenmodes in a slab plasma with finite magnetic shear. The corresponding growth rates of both instabilities scale with the electron-ion collision frequency ν_{ei} as $\nu_{ei}^{1/2}$.

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Numerical Study of Strong Ion Ring Trapping Efficiency*

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The RINGA code[1,2] has been used to study the resistive trapping of strong ion rings. We simulate the injection of an ion beam from a magnetically insulated annular diode through a cusp-like magnetic field. The cusp imparts a rotation to the beam, thus forming a ring which propagates down the tank towards a magnetic mirror (of mirror ratio M_1), beyond which is a region of azimuthal wall resistors (of conductivity σ, determined by requiring the L/R time of a resistor to be roughly comparable to the transit time of the ring under the resistor), and finally a larger mirror (of mirror ratio M_2). The ring bounces between the mirrors while dissipating axial energy to the resistors, and is eventually trapped.

The trapping efficiency, defined as the percentage of particles finally trapped, is found to be governed by three parameters: M_1, σ, and N, the number of particles injected. The dependence on σ is not critical; the dominant effect is the interaction between the mirror field and the ring's self-field, and hence the important parameters are M_1 and N. For given values of σ and M_1, trapping efficiency rises with N, then peaks and begins to decline. Rings which did not trap at this value of M_1 were successfully trapped by either raising M_1 (for large N) or lowering M_1 (for small N), but trapping could not be achieved by keeping M_1 constant and varying σ.

Typical trapping efficiency is 99% for $N = 8.55 \times 10^{16}$ protons and $M_1 = 1.11:1$.

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A Linearized 3-D Hybrid Code for Stability Studies of Axisymmetric Field-Reversed Equilibria*

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We have developed a linearized hybrid simulation code suitable for application to the study of the low frequency ($\omega < \Omega_i$) stability of field-reversed equilibria, in particular those of ion rings and mirror configurations. The model is a generalization of the purely particle-in-cell system described previously.[1]

In addition to the energetic ion component modeled by discrete particles, a cold, uniform density background of ions is described by an ion fluid equation, and a complement of cold electrons (of density such that charge neutrality obtains) is described by an electron fluid equation. We neglect electron inertia and the displacement current. Collisions between background electrons and ions are modeled by a scalar collision frequency.

The equilibrium magnetic field and hot-ion charge density are obtained from the zero-order module, a complete $2\frac{1}{2}$ D magnetostatic particle code in itself. $\underline{\delta J}_{hot}$ is obtained from the first-order particle-code module, which advances particles along their equilibrium orbits and at the same time follows first-order particle displacements of fixed toroidal mode number ℓ, via $\underline{\delta \ddot{r}} \propto \underline{\delta E} + \underline{v} \times (\underline{\delta B} + (\underline{\delta r}\cdot\nabla)\underline{B}) + \underline{\delta \dot{r}} \times \underline{B}$, where all fields are evaluated at $\underline{r}(t)$. To implement the hybrid model, we solve the electron momentum equation for $\underline{\delta E}$ and obtain $\underline{\delta B}$, $\underline{\delta J}_e$, $\underline{\delta J}_i$ in terms of $\underline{\delta E}$ and quantities known from the previous timestep, using over-relaxation to solve the resulting equation.

Improved finite-size-particle shape functions have been developed (with continuous derivatives to reduce noise in the first-order calculation), and a new, improved method for obtaining quiet equilibria is employed, using a resistive term $-\sigma\partial A_\theta^{(0)}/\partial t$ to damp collective oscillations from the system.[2]

Alfven wave propagation using both fluid and particle modules has been verified. We are at present examining the behaviour of infinitely long layers in a background plasma.

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FINITE GYRORADIUS GUIDING CENTER HAMILTONIAN*

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The standard guiding-center Hamiltonian is valid only in the limit $\epsilon_\perp \to 0$, where $\epsilon_\perp$ is the ratio of gyroradius to magnetic scale length normal to the magnetic field. In some plasmas, e.g., in the Tormac sheath and in mirror machines, $\epsilon_\perp$ may be appreciable, and finite-$\epsilon_\perp$ corrections must be obtained for a proper guiding-center theory. Axisymmetric devices possess a second parameter $\epsilon_\parallel$, the ratio of the longitudinal bounce frequency to the gyrofrequency.

One may treat $\epsilon_\perp$ as a small parameter, though in these devices (where it may reach a value $\epsilon_\perp \sim 1/3$), one may need to proceed to higher order to obtain sufficient accuracy. The parameter $\epsilon_\parallel$ is a genuinely small parameter in all axisymmetric devices of current interest. In the limit $\epsilon_\parallel \to 0$, the problem has only one nontrivial degree of freedom (slab model), and can be solved exactly for arbitrary $\epsilon_\perp$.

We have established procedures for explicitly obtaining the finite $\epsilon_\parallel$, finite $\epsilon_\perp$, guiding-center Hamiltonian H, to arbitrary order in $\epsilon_\parallel$ and $\epsilon_\perp$, by purely canonical means. The dependence of H on gyrophase is iteratively removed by a new variant of Lie perturbative methods, tailored to this "near slab" problem. The initial finite transformation from position and momentum to action-angle variables is achieved, for arbitrary $\epsilon_\perp$, by a mixed-variable generating function. To explicitly effect this finite transformation, we have used another variant of Lie methods. This approach yields the expansion in $\epsilon_\perp$, and replaces the previously-used ordering in m/e .

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EQUILIBRIA AND COMPRESSION OF ION RINGS*

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Results of a detailed study of exponential-rigid-rotor equilibria and of adiabatic compression of ion rings are presented. The exponential-rigid-rotor equilibria[1] are found to fall into three general classes: (a) shallow solutions, (b) deep solutions requiring a radial wall, and (c) deep solutions which do not necessarily require a radial wall. The influence of untrapped particles which cannot exist in reality is investigated by truncating the ring particle distribution function. Significant changes in the equilibria occur even for relatively large aspect ratios, $R/a \simeq 5$, indicating that truncation is necessary for fusion-relevant models.

The equilibrium code was modified to calculate the adiabatic compression of ion rings in a low-temperature collisional background plasma in which plasma currents are negligible. Following Ref. 2, the equilibria during compression are fixed by the distribution function $F(I,P_\theta)$, where $I = \int drdz(H-H_*) \times U(H-H_*)$. F, I, and P_θ are invariant during compression. Thus, for a given F, the ring distribution function $f(H,P_\theta,\lambda)$ and the associated physical quantities can be computed directly for a desired compression ratio, λ. Compression sequences so far have been studied for 4 different forms of $F(I,P_\theta)$. Compression has been followed up to 10^2 times the initial B-field with field reversals up to 2.2. The results indicate that the field reversal tends to saturate. The mean ring particle energy and ring radius do not saturate. An initial energy spread of the ring particles generally increases faster than their mean energy. In some models a hollowing of the current distribution is observed for large compression ratios. The relative ring geometry may change significantly. Results will be presented both for conventional and imploding linear compression schemes.

*Supported by US-DOE under contract EY-76-S-02-2319.*000

1) D.A. Larrabee, et al., Cornell University Report FRL-3 (April 1978).
2) R.V. Lovelace, submitted to Phys. Fluids, Cornell University Report FRL-2; see also this conference.

NUMERICAL MODELING OF INWARD TRANSPORT IN MAGNETICALLY CONFINED PLASMAS

R. Englade, T. Antonsen and B. Coppi

We have incorporated the anomalous transport coefficients derived for the ion mixing mode[1] in a radial transport code which includes the well known neoclassical transport coefficients and neutral transport and ionization. In addition, we have included anomalous (outward) transport of electron energy and particles necessary to achieve steady state discharges that reproduce those observed experimentally. The basic parameters of the code were chosen so as to model the gas injection experiments in the Alcator tokamak. The functional dependence of the ion mixing mode transport coefficients was chosen so that the coefficients increased from zero to some large value, D_o (estimated by the quasilinear approximation in the familiar way) as the local temperature and density profiles passed from a linearly stable to unstable state. We found that the resulting profiles were fairly insensitive to the values of D_o in the upper part of the range within which D_o has been estimated. In general the heating of ions in the center of the plasma column combined with production of cold plasma at the edge was sufficient to excite the ion temperature gradient driven modes and carry plasma toward the center.

[1] T. Antonsen, B. Coppi, and R. Englade, paper presented at this meeting.

ION CYCLOTRON RESONANCE HEATING THROUGH THE SLOW WAVES: A SIMULATION STUDY*

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A simulation study of physical processes involved in ion cyclotron resonance heating (ICRH) for the branch of the slow waves (Alfven-ion cyclotron waves) is carried out utilizing a 1-2/2 dimensional magnetostatic particle code. We focus on the heating processes associated with a wave generated by a uniform external (nonplasma) pump field with k parallel to B_o; no study of how the pump field is related to external coils is made. The heating process associated with resonant ion cyclotron waves proves to be a complex set of different physical effects depending upon the system's parameters. We find three different heating regimes in the parameter space of the pump amplitude and wavenumber. In the low pump-amplitude regime the magnetic energy linearly increases in time. On the other hand, in the moderate pump regime it increases exponentially with t and so does the total energy; the heating rate (exponent) satisfies an empirical scaling law $\gamma_{heat} \propto B_p{}^2\exp(-\alpha k_p)$, where B_p and k_p are the pump magnetic field amplitude and wavenumber. When the pump is strong, the heating is explosive and accompanied by parametric scattering instabilities. In this case, the magnetic field energy goes like $(t_c - t)^{-3/2}$, while the total energy increases as $(t_c - t)^{-1}$, where t_c is the explosion time. Through most of the simulation runs the magnetic pressure and the particle pressure are out of phase contrary to prediction of Kaufman.[1] Large orbit perturbations and particle trapping may account for the difference.

*Work supported by USDOE and NSF.

[1]J. R. Cary and A. N. Kaufman, Phys. Rev. Lett. 39, 402 (1977)

INDUCED SCATTERING BY OSCILLATION CENTERS IN NONUNIFORM PLASMA*

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The phenomenon of induced scattering in plasma (nonlinear Landau damping) is analyzed using canonical transformation theory. According to the oscillation-center picture[1], induced scattering can be viewed as a resonant interaction between oscillation centers and their beat Hamiltonians, thereby circumventing the need to calculate third-order quantities. This viewpoint is justified and extended using Lie operator techniques.[2] The general case of nonuniform, relativistic, magnetized (Vlasov) plasma is considered; the form of the scattering matrix element is derived (it displays Debye screening explicitly), and the classical foundations of the Manley-Rowe relations are clarified. The analysis exploits a simple relation[3] between the field-plasma interaction energy and the transformed single-particle Hamiltonian.

*Work supported by U.S.D.O.E. under contracts W-7405-ENG-48 and EY-76-S-02-2456.

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

2. R.L. Dewar, J. Phys. A. 9, 2043 (1976).

3. S. Johnston and A.N. Kaufman, Lawrence Berkeley Laboratory Report LBL-7253 (1978), submitted to Phys. Rev. Lett.

NEUTRAL-BEAM-DRIVEN CURRENTS IN TOKAMAKS

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ABSTRACT

The decrease in loop voltage that results from neutral-beam current induction in a tokamak plasma has been analyzed with a one-dimensional model that includes a Fokker-Planck analysis of the circulating ion current, the collisional electron shielding current, diffusion of electromagnetically induced currents, and the temporal evolution of the plasma electron temperature. If the total plasma current is kept constant, reversed loop voltages should be observable with intense beam injection into low-density plasmas in ISX-B and TFTR, which would provide unambiguous evidence of the beam-driven current. Steady-state operation at zero loop voltage should be possible with 40 MW of 80 keV H° injected tangentially into a 60-cm radius plasma in the proposed Superconducting Long-Pulse Experiment (SLPX). When the radial profile of the beam-driven current is less peaked than the ohmic-heating current profile, the effect of substituting beam-driven for ohmic heating current is to transform the profile of 'safety factor' q into one that is more stable to n=1, m=1 and n=1, m=2 kink modes.

Work supported by U.S. Department of Energy Contract EY-76-C-02-3073.

NEOCLASSICAL TRANSPORT IN THE ELMO BUMPY TORUS*

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There have been many investigations of radial transport in axially symmetric toroidal magnetic traps such as tokamaks where lowest order neoclassical transport is independent of radial electric fields. For axially asymmetric systems such as the bumpy torus, neoclassical transport depends sensitively on the ambipolar field, and radially resolved calculations including self-consistent ambipolar electric fields have not previously been attempted. Here we calculate neoclassical transport coefficients for the ELMO Bumpy Torus (EBT) for arbitrary radial electric fields, and we apply these coefficients in a one-dimensional radial transport model which includes the ambipolar field self-consistently. Previous neoclassical calculations for bumpy tori have treated only the large electric field limit[1] and transport in zero-dimensions.[2] Self-consistent, one-dimensional calculations are necessary to predict transport scaling and stability limitations for large fusion grade systems.

[1]L. M. Kovrizhnykh, Sov. Phys.-JETP 29, 475 (1969).
[2]C. L. Hedrick et al., Nucl. Fusion 17, 1237 (1977); J. B. McBride and A. L. Sulton, Nucl. Fusion 18, (1978).

*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.

POSTER SESSION REQUESTED

Should follow: "Banana Transport in EBT," by Hedrick, Spong, & Jaeger

POSTER SESSION

CALCULATED EFFECTS OF ASPECT RATIO ENHANCEMENT ON PARTICLE CONFINEMENT IN EBT*

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The toroidal curvature of the magnetic field in EBT results in an inward shift of particle drift orbits from the minor axis toward the major axis of the torus. The shift is largest for the transitional and passing particles, i.e., those with a large component of velocity parallel to the magnetic field.

A method of improving particle confinement in EBT through the addition of low current supplementary toroidal field coils called aspect ratio enhancement (ARE) coils will be presented. The improvements achieved with ARE coils include recentering the trapped particle drift orbits about the minor axis, increasing the useful bore of the torus, reducing the width of the loss cone, and improving the confinement of passing particles.

By varying the current in the ARE coils, the plasma geometry and effective aspect ratio can be varied, with the effect of either spoiling or enhancing plasma confinement. In addition to this increased flexibility and improved particle confinement in experimental devices, the addition of ARE coils should permit construction of a smaller EBT reactor without loss of performance.

*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.

DIRECT PARTICLE LOSSES IN THE ELMO BUMPY TORUS (EBT)*

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The ELMO Bumpy Torus (EBT) is comprised of a set of 24 toroidally linked mirrors. In conventional mirror machines, there are loss-regions in velocity space ($\mu \equiv v_{\parallel}/v > \sqrt{(R_m-1)/R_m}$) where the particles are not trapped by the magnetic mirrors; they escape by motion along magnetic field lines through the mirror throat. In EBT the untrapped particles of a single mirror become toroidally passing particles that contribute to a toroidal core plasma. Thus, there is no loss-cone as in a conventional mirror machine. However, there is a loss-region for pitch angles near the boundary between trapped and passing particles, provided the energy exceeds a critical value. It is caused by the fact that the (poloidal) precessional drift nearly vanishes for these particles. Such particles exhibit a vertical drift due to the R^{-1} falloff of the magnetic field, and in the absence of collisions, drift vertically out of the plasma confinement region. When Coulomb scattering is taken into account, the mean particle containment time against scattering into the loss-cone in a convential mirror machine is $\tau \sim \tau_{ii}\log_{10}R_m$. Here the logarithm arises from a solution of the diffusion equation governing pitch-angle scattering. In EBT the corresponding expression is significantly altered because the direct loss region is limited to energies above one of two critical values. One of the critical values occurs because the radial ambipolar electric field causes a poloidal E x B drift which confines low energy particles. Since magnetic drifts are proportional to energy, only when a particle energy exceeds a critical value can it escape the confinement region. A second contraint on energy occurs because collisions may scatter particles out of the loss region before they drift out of the plasma confinement region. Letting ε_c be the maximum of these energy cutoffs, the ion containment time associated with pitch angle scattering into the loss region is given by $\tau \sim \tau_{ii}(\log_{10}R_m)(\varepsilon_c/T_i)\exp(\varepsilon_c/T_i)$ and similarly for electrons. Taking into account energy scattering across ε_c reduces the direct loss life time by about a factor of two. Since typically $\varepsilon_c \gg T$, the direct loss life time is much larger than in a conventional mirror.

*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.

BANANA TRANSPORT IN EBT*

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While present neoclassical transport models for EBT are in reasonable agreement with experimental observations at low temperatures, they do not yield ion temperatures as high as those achieved experimentally. The source of the discrepancy appears to be the ion neoclassical transport coefficients used. Ion heat losses predicted are one to two orders of magnitude times the ion particle losses. This leads to low ion temperatures since the electron loss rates appear to dominate the particle and total energy losses.

Recently we have begun to improve the treatment of particle motion used in calculating neoclassical transport coefficients. The largest contribution to the ion neoclassical step size appears to be fron ions on the tail of the distribution for which the orbits are banana shaped. A simple Krook model indicates that the ratio of the ion energy to particle losses can be an order of magnitude less than the same ratio obtained from the earlier transport coefficients. This appears to be a good candidate for explaining the observed temperatures. More complete calculation of the transport coefficients is in progress and the status and results of these calculations 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.

EFFECT OF TENSOR PRESSURE ON TOKAMAK EQUILIBRIUM AND STABILITY*

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It is expected that intense neutral beam injection into tokamaks will produce an anisotropic equilibrium pressure tensor with, for example $p_{\parallel} >> p_{\perp}$. In addition to determining how this affects the equilibrium plasma shift and distortion of the flux surfaces, it is of interest to determine what effect $p_{\parallel} \neq p_{\perp}$ has on ballooning modes at finite beta. Expressions for the poloidal beta and current densities are obtained from the anisotropic equilibrium equation.

As a first estimate for the stability limit on beta, we model the tokamak as a segment of a cylindrical slab with fixed ends. This model demonstrates the essential features of an instability with finite $k_{\parallel}$ driven by toroidal curvature. A form of the Suydam stability criterion applicable to a tensor pressure plasma is evaluated to determine the upper bound on beta. The criterion is then altered to account for $k_{\parallel} \neq 0$, as in ballooning modes.

Finally, the ORNL 3-D MHD instability code has been modified to follow the double adiabatic equations for $p_{\parallel}$ and $p_{\perp}$ and to include forces from the pressure tensor. When $p_{\parallel} = p_{\perp}$ in the equilibrium, the instability results agree with those of ideal MHD. Work is in progress to pump $p_{\parallel} >> p_{\perp}$ and observe the effect on ballooning instabilities.

*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.

NUMERICAL STUDY OF DRIFT MODE BEHAVIOR USING A SELF-CONSISTENT DRIFT-KINETIC EXPANSION*

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In earlier work we have derived the perturbed distribution function for low-frequency drift modes in cylindrical collisionless plasmas, correct to first order in the $(k\omega/k_{||}\omega_p)^2 \equiv (\omega/\tilde{\omega}_p)^2$ series expansion for the self-consistent electrostatic field.[1] Starting with solutions of the linear dispersion relation, we now make numerical comparisons of the expansion solution for the electrostatic field with the Poisson solution, demonstrating that the expansion solution is indeed an average of the Poisson solution over ~ 50 of the modified plasma oscillation periods $2\pi/\tilde{\omega}_p$. We also investigate the nonlinear behavior of drift modes generated by moderately unstable solutions of the linear dispersion relation. The first harmonic initially excited in these calculations corresponds to a solution of the linear dispersion relation with a frequency approximately equal to that of the fundamental mode but with a much larger growth rate. After several oscillations the linear behavior of these modes is rapidly dominated by strong nonlinear effects. The numerical calculations are made using the Collisional Plasma Model drift-kinetic equation solver code DKES.[2]

[1]C. O. Beasley, Jr., H. K. Meier, W. I. van Rij, and J. E. McCune, Bull. Am. Phys. Soc. 22, 1166 (1977); Plasma Phys. 20, 115 (1978).
[2]C. O. Beasley, Jr., H. K. Meier, R. W. McGaffey, and W. I. van Rij, ORNL-5275 (June 1977) p. 121.

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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.

PRE-IGNITION PLASMA STUDIES OF SMALL HIGH-FIELD OHMICALLY HEATED TOKAMAKS *

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ABSTRACT

Studies have been made of the feasibility of attaining thermonuclear ignition in a small high-density high-magnetic field tokamak reactors heated solely by ohmic heating. We have used both the 1-D reactor code MAK1 and a simple point model to determine viable regions in parameter space, scaling, and parametric sensitivities of such a reactor. The codes use a transport model based upon neoclassical plus anomalous transport. They have been benchmarked against Alcator-A data. Results of the studies show that within the large uncertainties present in transport coefficients and scaling it may be possible to reach ignition in an ohmically heated tokamak having parameters R = .57 m., a = .22 m, B = 15.75 T, and I = 3.33 MA., the parameters of the proposed RIGGATRON (PHIBEX) experiment.

*Work supported by INESCO under contract S003-4068.

LARGE-SCALE PLASMA SIMULATION ON THE CHI COMPUTER*

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Three large plasma simulation models are being run on the recently installed Culler-Harrison, Inc. (CHI) computer:

(1) A 2½-dimensional electrostatic particle code with constant magnetic field plus mirroring. Runs of one half million particles have been made, using two of the four disks, at a speed of 30 μsec per particle update. Energy is conserved to within 0.3 parts per million per timestep, and within 2 parts per million for a run of 512 timesteps. Four-disk operation will allow 2.6-million-particle runs, at an expected speed of 15-20 μsec per particle update. The corresponding IBM 360/91 time is 55 μsec for assembly-language source code.

(2) A 2½-dimensional MHD fluid code with spatially dependent resistivity. Grids as large as 100 × 20 have been used, at 44 μsec per gridpoint update. The corresponding IBM 360/91 time is 160 μsec for Fortran-H source code.

(3) A 3-dimensional MHD fluid code with constant resistivity. Runs for a 16 × 16 × 24 grid have been made, without use of disks, at a timing of 83 μsec per gridpoint update. Use of disks will allow a 500 × 60 × 60 grid, at expected times of approximately 100 μsec per gridpoint update. The corresponding IBM 360/91 time is 230 μsec for Fortran-H source code.

*Work supported by USDOE.

Toroidal Effects on Lower Hybrid Wave Propagation*

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In toroidal geometry, the equilibrium magnetic field does not lie in the lower hybrid surface, $\omega = \omega_{LH}(\underset{\sim}{r})$. As a consequence, cold lower hybrid waves can be reflected from the lower hybrid surface rather than encountering a resonance there. Using a toroidal ray tracing code, we find that the ray makes successive bounces off the lower hybrid surface converging toward the meridian plane of the torus.[1] The addition of thermal effects can, however, have a dramatic effect on this phenomenon. With sufficient thermal effects included, the ray trajectory code indicates a picture similar to that obtained in planar geometry, i.e. mode conversion to a hot plasma wave which then propagates outward. The integrated effects of electron and ion resonant particle damping along the ray are included in the ray code, and will be used to assess the spatial distribution of energy deposition.

*Work supported by U.S. Department of Energy Contract #EY-76-S-02-3170.

1. E. Ott, J.-M. Wersinger, and P. T. Bonoli, Cornell University Laboratory of Plasma Studies Report #234 (1977) (to be published in Phys. Fluids); K. Connor and P. Colestock, Proc. 3rd Conf. on RF Plasma Heating (Pasadena, CA, Jan. 1978).

NONLINEAR THEORY OF DRIFT CYCLOTRON MODES IN MIRROR MACHINES

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We study the effect of nonlinear frequency shift on the saturation of the resonant drift-cyclotron loss cone (DCLC) instability and the spatial and temporal evolution of the wave amplitude, extending the previous analysis including only the temporal variations.[1]

Starting from the partially-filled ion loss-cone distribution function:

$$f_0=[(1-\Delta)f_M+\Delta/\pi(V_\perp^2/V_i^4)\exp(-V_\perp^2/V_i^2)][1+(x+v_y/\Omega_{cc})/L] \quad (1)$$

where f_M is a Maxwellian in the perpendicular velocity variable $V_\perp$, and Ω_{ci} is the ion cyclotron frequency. For $1>>\Delta>>(L/\bar{\rho}_i \overline{m}/M)^{1/2}$, with $\bar{\rho}_i=V_i/\Omega_{ci}$, we find a linear growth rate $\gamma_0\sim\Delta^{1/2}\Omega_{ci}$, and nonlinear saturation at a low level $e\phi/T_i\approx\Delta^{1/2}(\rho_i/L)^2$. Allowing nonlinear frequency shift, the following nonlinear partial differential equation for the amplitude of the potential is obtained

$$\left(\frac{\partial^2}{\partial t^2}-\frac{\partial^2}{\partial y^2}\right)\phi+i|\phi|^2\left(\frac{\partial}{\partial t}-\frac{\partial}{\partial y}\right)\phi-\gamma_0^2\phi=0 \ . \quad (2)$$

We have studied this nonlinear equation by the inverse scattering method. Infinite number of global conservation laws are found, for example, $E_1=\frac{1}{2}\int dy\left\{\left|\frac{\partial\phi}{\partial y}-\frac{\partial\phi}{\partial t}\right|^2-\gamma^2|\phi|^2\right\}$ is a constant of motion. Soliton solutions are obtained from the associated Gelfand-Levitan equations. They travel with speeds $|v|\geq1$. A self-similar solution is also obtained, which is found to dominate over the soliton solutions from a numerical study of the time evolution of an initial δ-function profile. Causality limits the wave front to propagate with speeds $|v|=1$ away from the initial localized region. Solutions with more realistic periodic boundary condition are also under study. For a smooth initial profile, solitons are expected to be the main ingredients which may explain the highly coherent structures observed in mirror machines.

1. R.E. Aamodt, Y.C. Lee, C.S. Liu, M.N. Rosenbluth, Phys. Rev. Lett. 39, 1660 (1977).

APPLICATIONS OF PLASMA GUNS TO PRODUCE FIELD REVERSAL*

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ABSTRACT

We discuss the use of coaxial plasma guns to produce field-reversed plasma "blobs" and applications of the blobs to confinement configurations for fusion. In this concept field-reversed blobs are projected from a coaxial gun through a magnetic cusp into an axial guide-field. The cusp is formed by an axial field inside the inner electrode of the gun which is oppositely directed to the guide-field. Accelerated plasma sweeps up the radial component of the inner conductor field, elongating it axially until tearing occurs. The plasma ring (which may have an azimuthal embedded field during acceleration) is thereby "swaddled" in closed poloidal flux. Numerical calculations of the formation will be presented.

A number of applications appear possible and will be discussed. Because of the high kinetic and total energy output of guns, multi-keV temperature blobs could be compressed and trapped for pulsed thermonuclear burn. Alternatively, trapping in static fields would provide a well matched target for a FLR stabilized, field-reversed configuration sustained by neutral beams. Another possibility is to employ the "blobs" to carry flux to sustain the fields of a stationary configuration fueled by neutral beams.

Trapping of the gun toroidal field can lead to a shear-stabilized, MHD-stable toroidal pinch configuration without a conductor on axis. Toroidal aspect ratios of order unity therefore appear possible but at smaller β than the FLR stabilized configuration.

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QUASI-STEADY MODELLING OF LASER HEATED PLASMA COLUMNS

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Long wavelength (10.6 μm) laser radiation has been used to heat relatively dense (10^{17} cm^{-3}), small diameter (5-10 mm), magnetically confined plasma columns. Axial propagation of the laser beam over distances exceeding several column diameters requires an electron density minimum on-axis to serve as a "light pipe". We examine the conditions under which laser heating produces such favorable density profiles. At high temperatures laser heating maintains the light pipe despite particle diffusion,(1) however in the cool formation phase treated here, diffusion may be rapid.

We use the one-dimensional (in radius), two-fluid, quasi-static Lagrangian code developed by Willenberg.(2) Particle-field diffusion is classical with thermoelectric (TE) effects included in the energy and field diffusion equations. Low-temperature, low-$\omega\tau$ effects are included in the transport coefficients. In contrast with high temperature plasma columns where the thermal diffusivity exceeds the particle diffusivity, laser heated plasmas can initially have steep electron temperature profiles. TE terms then become important and "push" particles into the hot column center. This makes it difficult to maintain an on-axis density minimum during the early stages of heating. At later times and higher temperatures the TE effect becomes favorable and reinforces the conclusions of Ref. 1. Numerical examples are given and correlation is made with analytic scaling arguments. Comparison is also made with experiments currently in progress at Mathematical Sciences Northwest, Inc.

Ref. 1 H.A. Bethe, and G.C. Vlases, Phys. Fluids, 18, 982 (1975).
Ref. 2 H.J. Willenberg, submitted to Nuclear Fusion.

AXIAL HEATING OF LINEAR MAGNETIC FUSION SYSTEMS

by

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The heating of linear magnetic fusion systems by collisional damping of strong axial magneto acoustic waves has been studied with a numerical model which includes radial and axial MHD, physical viscosity, and separate electron and ion temperatures and thermal conduction. Increases of plasma temperature by about a factor of 1.5 to 2.0 are seen on each cycle of the low frequency external magnetic pumping field which produces the axial waves. Parameter studies of heating rate as a function of axial wavelength and frequency of the pump field will be shown. It is shown that this heating method could be an effective and economical alternative to radial shock heating in linear magnetic fusion reactor systems.

Numerical Simulation of Reversed Field Buildup in a Mirror Machine †

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We report on the development of a numerical code which simulates the buildup and evolution of a reversed field region in a mirror machine. The theoretical background is discussed by Grad et al.[1] Two transport variables equivalent to P and T are advanced in time on the correct transport time scale. The geometrical coefficients in the 1-D transport equations vary piecewise linearly with time and are obtained from the 2-D geometry which is evaluated at a sequence of points in time. At these times, the transport profiles are used to construct the right hand side of the Grad-Shafranov (GS) equation; its inversion gives the geometric coefficients as contour averages. This is an iteration on the geometrical coefficients, $K = \langle|\nabla V^2|/r^2\rangle$ and $S = \langle r^2\rangle$ at the advance time, assuming that they are known at the initial time. Diffusion is carried out in 1-D with K and S linear in t. The diffusion profiles at the advance time give a new advance set of K and S, and the diffusion is repeated until it settles down self-consistently.

There is a fairly complex system of transferring information among meshes, viz. the 2-D (x,y) mesh, the 1-D contour mesh (volume), the 1-D diffusion mesh (mass), and the "background" mesh used to transfer between mass and volume (as a function of time, since the density is varying).

The appearance of islands (reverse field regions) is treated as follows. After an island is observed to be larger than a preset small volume, the geometry data is evaluated, tabulated, and interpolated in time separately for each region.

A summary of results to date will be given.

1. H. Grad, et al.,"Macroscopic Transport Model for a Reversed Field Mirror Machine" in the proceedings of this conference.

† Work supported by U.S. DOE, Contract No. EY-76-C-02-3077.

A Treatment for Plasma Buildup in a Small Mirror Fusion Device*

by

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In a small mirror plasma ($R_p/\rho_i \leq 40$) finite gyro-radius (F.G.R.) effects become important, particularly at the surface near the vacuum interface. This is because charge-exchange of incoming cold neutrals (from injector and recycling off the first wall) occurs primarily in a surface layer only a few centimeters thick, causing plasma erosion and possible collapse.[1,2]

Modeling a small mirror plasma during buildup is very (computer) time consuming if either Monte Carlo or 3-D. Multispecies Fokker-Planck techniques are used. A faster, modified Fokker-Planck code is under development (called FORMD) which models the plasma with energy and spatial grids using finite differencing techniques. Finite orbit effects are treated by finding the time-averaged density contribution of gyrating particles to each plasma region. Included are ions with noncircular orbits (due to large magnetic field gradients) and F.G.R. effects on beam deposition.

This code will be used to model devices such as MFTF (FERF)[2,3], TMX[4] and the Twin-Beam Mirror (T.B.M.)[5]. Some results for a high energy mirror plasma will be presented, if time permits.

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1. Stallard, B. W., "Radial Plasma Buildup Code for Neutral Beam Injection into a Mirror Machine," *UCRL-51784* (1975).
2. Campbell, M., "Recent Studies Concerning Plasma Buildup in a Mirror Fusion Test Facility (FERF)," *UCID-17458* (1977).
3. Batzer, T. H., et al., "Conceptual Design of a Mirror FERF," *UCRL-51617* (1974).
4. Logan, B. G. and Miley, G. H., *Proceedings 2nd IEEE Minicourse on Fusion*, Troy, N. Y. (1977), chapter 8.
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*Work supported by U. S. Department of Energy.

HYBRID MODEL SIMULATION OF THOR*

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The anomalous resistivity model of Liewer and Krall[1] has been incorporated into the hybrid code of Sgro and Nielson[2] and the resulting program was used to study θ-pinch implosions in the parameter regime of the University of Maryland toroidal θ-pinch, Thor. The model has cylindrical geometry, one dimension, fluid electrons, Vlasov ions, and includes multistep ionization processes and the production of neutrons. The microinstabilities included in the anomalous resistivity and heating are Buneman two-stream, ion acoustic and lower hybrid.

The external radius is 20 cm, initial central densities are $1\text{-}3\times10^{14}\,\text{cm}^{-3}$, initial temperatures are 1-2 eV. The magnetic field has peak values of 6.0, 8.0, and 9.3 kG and is crowbarred at 0.9 μs. The final electron temperatures obtained are in the 200-300 eV range, in agreement with recent measurements (Thomson scattering) of bulk electron temperatures in Thor. The previously reported keV electron temperatures (x-ray measurements) are due to a small population (1%) of suprathermal electrons. Peak ion temperatures of 1-3 keV are observed which are in the range of the experimental results. These peaks occur during the instants of maximum compression (plasma radius around 6 cm). Emission of neutrons also occurs during these peaks (about 10^6 neutrons per shot, again in the experimental range). The initial ion density profile is of the form $n_N=n_0\exp[-(r/a)^2]$, with a=13 cm. Two neutral particle profiles were used: $n_N=n_0[1-\exp(-(r/a)^2)]$ and $n_N=0.2\,n_0$, a constant. In both cases the speed of the magnetic piston is too high, but much more so when $n_N=0.2\,n_0$. This suggests an even higher neutral density at the walls. It is possible that these neutrals are generated by charge exchange during the pre-heating stage and are then cooled by the walls.

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NUMERICAL STUDIES OF NONLINEAR MHD PROPERTIES OF A FINITE-BETA PLASMA AND COMPARISON WITH EXPERIMENT*

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The internal properties of internal kink modes in a rectangular, finite-β plasma are studied using a 3D MHD initial value code. This fully nonlinear code follows the time evolution of the density, momentum, pressure, and vector potential. Compressional effects are not ordered out since β is finite. The dependence of these effects on aspect ratio and β is being studied. Results from this code have been compared with the TERP experiment at the University of Maryland.[1] This experiment is characterized by a paramagnetic toroidal field profile, $\beta_{pol} \approx 0.67$, and high beta, $\beta_t(\text{axis}) \approx 0.1$-$0.3$.

In the past, good quantitative agreement was obtained between the experiment and ORNL 2D linear MHD code for the growth rate and the $\beta_t(\text{axis})$ at which initial onset of the instability occurs ($\beta_t \approx 0.12$). Comparison of results from the nonlinear code and the experiment shows good qualitative agreement on several important features: in both the experiment and the model, the growth rate evolves from a constant value (linear phase) to a value decreasing in time during the nonlinear phase. The perturbed poloidal field on axis increases exponentially during the linear phase and then falls off at later times. The length of the linear phase in the model and the experiment are roughly the same ($t \approx 20\ \tau_A$). Additionally, both the computed and measured profiles show the development of steep density gradients. In an attempt to simulate the wall effects of the TERP experiment, a spatially varying velocity drag term has been added to the momentum equation. This term has the effect of inhibiting flow near the walls.

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HYBRID STABILITY PROPERTIES OF A CYLINDRICAL ROTATING P-LAYER IMMERSED IN A UNIFORM BACKGROUND PLASMA*

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The generation and application of intense ion beams to produce field-reversed configurations have received considerable recent experimental[1,2] and theoretical[3] attention. The electrostatic stability properties of a rotating, charge-neutralized P-layer are investigated within the framework of a hybrid (Vlasov-fluid) model in which the layer ions are described by the Vlasov equation, and the layer electrons and the uniform background plasma are described as macroscopic, cold fluids. It is assumed that the P-layer is thin, with radial thickness (2a) much smaller than the mean radius (R_0), and that $\nu \ll 1$, where ν is Budker's parameter for the layer ions. Moreover, electrostatic stability properties are calculated for perturbations about a P-layer with rectangular density profile, described by the equilibrium distribution function $f_b^0=(n_bR_0/2\pi m_i)\delta[H-V_zP_z-m_i(V_0^2-V_z^2)/2]\delta(P_\theta-P_0)$, where H is the energy, P_θ is the canonical angular momentum, P_z is the axial canonical momentum, and n_b, R_0, V_z, V_0, and P_0 are constants. The stability analysis is carried out including the effects of a uniform background plasma, and weak self magnetic fields. Although a slow rotational P-layer ($P_0>0$) is found to be stable, it is shown that a fast rotational P-layer ($P_0<0$) is unstable for sufficiently high background plasma density ($\omega_p^2 \gg \omega_{ci}^2$). The typical instability growth rate is a substantial fraction of the ion cyclotron frequency. Finally, preliminary Vlasov-fluid stability results are presented for the case of an intense proton layer immersed in a plasma background, with arbitrary degree of field reversal.

*Supported by NSF and ONR.

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RF Runaway in an Ideal Lorentz Plasma*

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The presence of RF energy in a plasma for which electron-electron collisions may be ignored, e.g. when Z_{eff} is very large, results in a runaway of the tail of the electron velocity distribution[1] even in the absence of a DC electric field. This is because the resonant electrons absorb energy from the RF waves but cannot dissipate it, since collisions with fixed-center ions scatter momentum but not energy. In calculating the time-evolution of the two-dimensional electron velocity space distribution, we find two useful limiting cases, very strong and very weak velocity space diffusion caused by the RF relative to the diffusion caused by electron-ion collisions. In the former case, which, of course, always obtains at advanced stages of the runaway phenomenon, the edge velocity of the runaway distribution scales as $u_e \sim t^{1/6}$. In the earlier stages of the runaway, when the latter case may be relevant, the runaway edge velocity scales as $u_e \sim t^{1/5}$.

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Resistive Ballooning Modes in Toroidal Plasmas*

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There has been much interest recently in ideal MHD ballooning modes with large toroidal mode number n, which become unstable for $\beta \sim 5\%$[1]. We consider resistive ballooning modes which have the same relationship to ideal ballooning modes as tearing modes[2] have to kink modes. Their growth rate s scales as $(\eta n^2)^{1/3}$, where η is the resistivity. They will lower the critical β, perhaps even to a point where they can account for the observed high density limit in tokamaks. We derive a fourth-order set of ordinary differential equations in which the independent variable θ goes from $-\infty$ to ∞ as it follows a field line around an ergodic surface. The limit of these equations as $\theta \to \pm\infty$ exhibits qualitative changes when η and $s \to 0$. This leads to a transition region for $\theta \sim (\eta n^2)^{-1/3} >> 1$, analogous to the singular layer of a tearing mode. The equations governing this transition region are the Fourier transforms of the tearing layer equations. Matching their solutions onto the ideal marginal solutions for $\theta << (\eta n^2)^{1/3}$ leads to a dispersion relation analogous to that for tearing modes.

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The Complex Modified Korteweg-DeVries Equation Describing the Nonlinear Propagation of a Lower Hybrid Ray*

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For large amplitude electrostatic lower hybrid waves, when nonlinear effects due to selfmodulation are important, the steady state propagation can be described[1] by the complex modified Korteweg-DeVries(CMKDV) equation, $v_\tau + v_{\xi\xi\xi} + (|v|^2 v)_\xi = 0$, where v is proportional to the electric field and ξ and τ are spatial coordinates. The interesting solutions to this equation are those for which v is complex[2], and in this case the equation does not appear to be analytically soluble. We have undertaken a numerical study of the complex solutions of the CMKDV equation. The results show that a pulse may break up into either real solitary pulses or envelope pulses or both. Collisions between these pulses are inelastic in general, distinguishing them from solitons. The envelope pulses are a generalization of the solitons of the nonlinear Schrödinger (NLS) equation, to which the CMKDV equation reduces in the limit of a narrow spectrum[3]. We find that there is an additional condition on the amplitude of the initial pulse which must be satisfied before the NLS equation applies and that even under these conditions the corrections to the NLS equation make solitons with the same central wave number move apart. Thus self-focusing is not likely to occur. The real solitary pulses are related to the solitons of the real modified Korteweg-DeVries equation. Their appearance in the break-up of a pulse points to the occurrence of nonlinear internal reflections, and necessitates re-solving the CMKDV equation as a boundary value problem. We present calculations of the reflection coefficient.

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Effect of Non-Diagonal Resistivity*

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The standard Ohm's law is $\vec{E} + \vec{v} \times \vec{B}/c = \overleftrightarrow{\eta} \cdot \vec{j}$. The resistivity $\overleftrightarrow{\eta}$ is classically diagonal in a magnetic coordinate system with two independent components $\eta_{\parallel}$ and $\eta_{\perp}$. However, the general tensor $\overleftrightarrow{\eta}$, we will show, has four independent components. The two additional components give a bootstrap current and a pinch similar to the Ware pinch. Plasma microturbulence can produce an effective resistivity of the general form and hence strong pinch and bootstrap effects.

To understand the general form for $\overleftrightarrow{\eta}$, one notes that $\vec{\nabla} p = \vec{j} \times \vec{B}/c$ implies $\vec{j}$ has only two finite components, for the third is zero. The component of $\vec{E} + \vec{v} \times \vec{B}/c$ in the direction of the pressure gradient gives the plasma rotation and is not relevant to transport. Consequently, $\overleftrightarrow{\eta}$ transforms one two dimensional vector, $\vec{j}$, into another, $\vec{E} + \vec{v} \times \vec{B}/c$. This means $\overleftrightarrow{\eta}$ can have only four components. Writing Ohm's law in component form, one has $E_{\parallel} = \eta_{\parallel} j_{\parallel} - \eta_B j_{\perp}$, $E_{\perp} - v_r B/c = \eta_{\perp} j_{\perp} - \eta_p j_{\parallel}$, and $dP/dr = j_{\perp} B/c$. Trivial algebra gives

$$j_{\parallel} = \frac{E_{\parallel}}{\eta_{\parallel}} - \frac{\eta_B}{\eta_{\parallel}} \frac{c}{B} \frac{dP}{dr} ,$$

$$v_r = \frac{cE_{\parallel}}{B} + \frac{\eta_p}{\eta_{\parallel}} \frac{cE_{\parallel}}{B} - \frac{\eta_{\perp}\eta_{\parallel} - \eta_B \eta_p}{\eta_{\parallel}} \frac{c^2}{B^2} \frac{dP}{dr} ,$$

which demonstrates the pinch and bootstrap effects produced by finite η_p and η_B. If the microturbulent plasma obeyed Onsager's relations, then the resistivity would be symmetric and $\eta_p = \eta_B$. In the long-mean-free path limit of a toroidal plasma (banana regime) the electron parallel viscosity produces an effective η_p and η_B giving the well-known pinch and bootstrap effects.

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Theory of Drift and Trapped-Electron Instabilities in Tokamak Geometry*

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This paper deals with the linear theory of low-frequency drift and trapped-electron instabilities in tokamak geometry. In particular, results are presented for the first completely 2-D toroidal calculations of trapped-electron modes (as well as collisionless and collisional drift-waves), including the slow spatial variation in equilibrium quantities and their gradients, and valid for arbitrary wavelengths. In order to properly assess the danger of these instabilities for tokamak confinement, it is essential to take into account the fully 2-D nature of the axisymmetric toroidal geometry. This fact has been underscored by recent calculations which have shown that the familiar universal (collisionless) drift modes are actually stable in a simple slab geometry with shear, if the proper nonresonant electron response is taken into account. These results have been reproduced in the present 2-D calculations by suppressing the toroidal terms in the basic eigenmode equation. In addition, since the present analysis is valid for arbitrary wavelengths, it was possible to extend the earlier long wavelength ($k_r\rho_i < 1$) calculations to the short wavelength regime ($k_r\rho_i \gtrsim 1$). The main conclusion here is that the drift modes apparently remain stable in a slab geometry even when the usual second-order differential equation becomes invalid. In toroidal geometry, however, the picture is quite different. To treat this 2-D problem the general approach here is to convert the integral eigenmode equation into a matrix equation, by expanding the perturbed electrostatic potential $\tilde{\Phi}$ in complete sets of appropriate radial and poloidal basis functions. However, unlike earlier calculations, the slow radial variation in equilibrium quantities and their gradients is now taken into account. This new feature enables us to realistically study the large-scale radial localization of the eigenmodes. Using representative profiles from PLT and ALCATOR, the computed characteristics of the eigenfunctions are found to be in reasonable agreement with features of the measured fluctuation spectra. In addition, reasonable agreement, both in features of the mode structure and estimates of the growth rate, are found when the calculated results are compared with corresponding results obtained during the linear phase of recent 3-D toroidal simulations of trapped-electron modes.

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A Thermodynamic Approach to Dissipative Drift Instabilities*

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The transport of electrons and energy across a plasma slab associated with various dissipative drift instabilities (e.g., the dissipative trapped electron instability) is examined. A single electrostatic wave is considered. Equations describing the evolution of the plasma number density, momentum density, energy density, and entropy density are derived from the drift kinetic equation, while an equation for the evolution of the wave amplitude is obtained using the local approximation. The (possibly nonlinear) growth rate of the wave is found to be directly related to the electron flux. This connection between the wave growth and the electron flux is interpreted as a consequence of momentum conservation; this allows a simple and direct estimate of the growth rates of the various dissipative drift instabilities. In addition, it is shown that, when the thermodynamic forces are properly identified, the drift wave transport coefficients derived by previous authors do indeed satisfy the Onsager realtions, and that the resulting plasma transport produces a net increase in the plasma entropy.

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ALPHA-PARTICLE COUPLING IN LINEAR MAGNETIC FUSION PLASMAS

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An ignited fusion plasma description is constructed for α-particle coupling with a linear, magnetically-confined plasma column, accounting for α-particle slowing down and endloss, radial and axial plasma structure, radial plasma transport, and endloss of particles and energy from the plasma. The ignited plasma description is based on a solution to the Fokker-Planck (FP) equation for α-particle transport. The FP model accounts for α-particle birth due to fusion reactions, gyroradius excursions outside the finite-radius plasma column, endloss through a loss cone, slowing down due to drag against electrons and ions, and polar angle scattering due to collisions with electrons and ions. The equation for the distribution function f is linear in the leading terms and admits a normal mode analysis: this analysis separates the polar angle dependence (a second order equation in ϕ), from the energy-time dependence (a first order equation in energy, U, and time, t). Solution to the ϕ equation is governed largely by the loss cone angle. The resulting expression for $f(U, \phi, t)$ is dominated by the fundamental mode.

The fundamental mode behavior of the FP solution is used to formulate a simplified description of α-particle dynamics. The fusion plasma (DT) model is a zero-dimensional time-dependent decription containing modelled effects of radial and axial structure and transport processes. The combined α-particle and DT plasma models are used to compute the behavior of ignited linear plasmas, with particle and energy endloss.

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PROPAGATING-BURN START-UP OF IGNITED TOKAMAK PLASMAS

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ABSTRACT

The neutral-beam voltage and power requirements for heating a tokamak plasma to ignition can be minimized by first "overheating" an undersized plasma, then compressing it, and finally allowing the compressed fusioning core to burn into a dense cold plasma blanket until ignition size is attained. This technique can also insure ignition if impurity influx into the unprotected beam-heated plasma cannot be avoided.

We have investigated the properties of propagating burns using both an analytic model and a 1-D radial transport code. The analytic model assumes constant temperature inside the fusioning core, and zero temperature but very high density outside the burn front. Heat flows into the burn front from the core at the "empirical" energy diffusion rate, while the density builds up in the core to keep the pressure at the MHD-limiting value. The initial impurity concentration in the core is rapidly diluted. The core energy content decreases until the expanding plasma is sufficiently large to satisfy the equilibrium ignition condition. In this way, stationary ignited plasmas are obtained from beam-heated compressed plasmas whose initial $n\tau_E$ is significantly less than that required for ignition, but whose initial temperature is 15 to 25 keV.

The usefulness and limitations of the idealized analytic model are investigated by comparison with 1-D transport code simulations.

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NUMERICAL SIMULATION OF IMPURITY TRANSPORT IN ISX*

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In the ISX impurity flow reversal experiment, there is strong evidence for a flow reversal of injected neon [1]. We have numerically simulated this experiment by including the axymmetric proton source term [2] in our impurity transport code [3]. We used neoclassical diffusion coefficients but doubled the self diffusion term. For the plasma distribution we used the experimentally measured $T_e(r)$ and $n_e(r, t)$ except for a slight modification of $T_e(r)$ near the edge. Z_{eff} is 1.5. The neutral neon atoms are taken to have room temperature thermal energy (0.025 eV) and their ionization and diffusion are followed numerically. The calculated evolution of the line integrated neon VIII line intensity agrees with experiment after the observed $T_e(r)$ is slightly modified in the edge region. The calculated relation between the neon flow reversal rate and the H_2 injection rate agrees approximately with the experimental relation.

In ISX also, some effects of a high-Z limiter were simulated by a tungsten injection which produced significant supression of central T_e [1]. We are currently simulating this experiment.

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Alfvén Wave Heating in General Toroidal Geometry

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The purpose of this paper is to analyze Alfvén wave heating of plasmas in general toroidal geometry. The theory of Alfvén wave heating centers about spatial singularities of the linearized ideal MHD variables, reflecting accumulation of energy. For inhomogeneous equilibria with sufficient symmetry, two decoupled singular modes appear: the Alfvén mode and the cusp mode. However, in the absence of symmetry, these modes are coupled and form a new system of spatial singularities. The singular surfaces are identical with the equilibrium magnetic surfaces and do not in general coincide with surfaces of constant Alfvén speed. Moreover, the frequency of the singular modes is obtained as an eigenvalue of a partial differential operator with respect to angle coordinates spanning a given magnetic surface. In this paper we present a rigorous analysis of the absorption process associated with the singular modes in general toroidal equilibria. We introduce curvalinear flux coordinates and obtain a system of coupled partial differential equations for the linearized total pressure and the contravariant components of the plasma velocity and the perturbed magnetic field. The singular modes obtained from this system are shown to be characterized by logarithmic singularities in space, analogous to the singularities of the screw pinch[1] and axisymmetric toroidal equilibria.[2] The coupling of an external energy source to the singular solution is described as well as the computation of the rate of energy accumulation in the singular layers. It is demonstrated that an optimum current source for energy absorption is associated with each singular solution.

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AXISYMMETRIC TRANSPORT IN TOKAMAKS*

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In a series of numerical models we have embodied ideas about axisymmetric transport suggested by Harold Grad for the evolution of tokamak plasmas to high-β states. The problems studied with these models range from an evaluation of the predictions of popular empirical scaling laws under conditions of intense beam heating, to the self-consistent investigation of the nature of collisional, time-dependent transport at arbitrary β.

The Oak Ridge Tokamak Transport Code employs a formulation for axisymmetric transport which is suitable for evaluating and extrapolating models suggested by experiments or models based on estimates from plasma kinetic theory. This code treats the motion of (toroidal) flux contours by an implicitly Lagrangian method, and accepts postulated models, assumed local to a flux surface, for the cross-surface transport rates. Studies of the ATC and TUMAN compression experiments and neutral beam heating results show that this approach is adequate for a limited range of extrapolation. Such effects as beam deposition in a noncircular geometry and of beam pressure on equilibrium and stability, and the evolution of neutral gas and impurity processes have been studied with this model.

A second method is used to solve the collisional particle, energy, and field equations self-consistently to determine the plasma transport--both convective and diffusive. It represents an extension of Pfirsch-Schlüter transport to the fully time dependent case at arbitrary β and aspect ratio. The total fluid velocity can be solved analytically and all time-dependent transport coefficients are displayed explicitly. The resultant transport can differ significantly from the Pfirsch-Schlüter rates.

Both methods solve one-dimensional transport equations coupled with two-dimensional equilibrium solutions of the Grad-Shafranov equation [1], and thus are not significantly more costly than conventional radial transport calculations.

[1] ADIABAT Code courtesy of D. C. Stevens, Courant Institute.

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BALLOONING MODES IN HIGHLY ELONGATED TOKAMAKS*

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Ballooning modes are studied in highly elongated toroidal plasmas with fixed boundaries. Computational studies have indicated that even mildly diamagnetic plasmas ($\beta_{pol} > 1$) are unstable to ballooning modes if the toroidal current profile is broad enough so that the inner flux surfaces are highly elongated. In spite of the fact that the toroidal current concentrates near the outer edge of the toroidal plasma, we have shown that the pressure gradient rather than the parallel current provides the main driving force for these instabilities away from the magnetic axis. A cylindrical slab model can be used to study these modes in more detail using non-ideal MHD models. In particular, the effect of "collisionless" ("parallel") viscosity is studied. While the true marginal stability point is not changed, viscosity can reduce the growth rate of the instability by orders of magnitude unless the flow pattern of the instability conforms to the functional null space of the viscosity operator. Using this constrained velocity field, a new effective marginal point is obtained.

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THE TOPOLOGY OF LARGE BANANA-WIDTH TOKAMAK ORBITS*

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To properly understand neutral injection or α-particle heating in large banana width systems, a detailed knowledge of guiding center orbits is required. Previous treatments of such orbit-related topics as beam deposition, loss-regions and wall loading have relied on large amounts of computational effort to account for the possible orbits, birth points in the plasma, pitch angles, and energies of interest. These approaches become increasingly more difficult when high β, non-circular plasmas are involved. These problems can be systematically treated by proper categorization and description of the orbits.

In an axisymmetric tokamak, each guiding-center orbit is completely described by a point in a three-dimensional "constants of motion" space. In particular, we choose the speed (v), the maximum value of poloidal flux along the orbit (ψ_m), and the value of $v_\parallel/v$ at $\psi_m(\zeta)$. The various types of orbits (banana, circulating, stagnation, etc.) can be depicted by different regions and surfaces in this space. In this space, each orbit is represented only once, and the loss-regions are easily and fully represented. Beam deposition and the complete fast ion slowing down problem may be more easily done in the constants of motion space.

Some preliminary results of this detailed analysis are: 1) for high enough energies, no particles are trapped, 2) particles with pitch angles of 90° are barely trapped, 3) particles can go from being "co" to being "counter" only by scattering through the orbit on which the points of the banana meet, 4) all topological properties of the orbits depend only upon $B(\psi)$, $F(\psi)$, and their ψ derivatives on the equatorial plane.

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PELLET INJECTION MODEL AND COMPARISON WITH ISX*

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A computer routine, PELLET, has been developed for modeling pellet injection in tokamaks. PELLET can be coupled to 1 or 1½-D tokamak transport codes to give particle deposition profiles as a function of pellet size and velocity. The effects of non-concentric, shifted flux surfaces are included in the deposition profiles. Preliminary calculations give qualitative agreement with ISX-A results: The initial density increment observed when pellets are injected into ISX-A is consistent with the total number of particles contained in the pellet. In the model, the plasma temperature is decreased adiabatically by the introduction of cold fuel, giving a corresponding increase in plasma resistance and predicting a positive voltage spike. The voltage spike is seen experimentally. The observed penetration depth is consistent with an ablation model developed by Milora and Foster [1] from whose work PELLET has evolved. Sample calculations and experimental data will be presented.

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Perturbation of the Alfvén Wave Continuum by the Hall Effect

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The objective of this analysis is to determine the influence of the Hall effect on the Alfvén wave continuum of ideal MHD. The Hall effect introduces the ion cyclotron frequency and allows analysis at frequencies higher than in ideal MHD. We assume a screw pinch equilibrium surrounded by a vacuum region and describe the plasma dynamics in terms of the linearized MHD equations with Ohm's law written in the form $\underset{\sim}{E} + \underset{\sim}{v} \times \underset{\sim}{B} = (\varepsilon/\rho)\underset{\sim}{J} \times \underset{\sim}{B}$, where ε is the ion mass to charge ratio. Assuming the linearized variables depend on time t and the cylindrical coordinates (r,θ,z) in the form $g(r)\exp i(\omega t-m\theta-kz)$, we obtain a fourth order system of ordinary differential equations for the linearized radial velocity u and the linearized total pressure p^* in place of the second order system of ideal MHD. This system has a turning point at the ideal MHD Alfvén wave singularities. We specify two further boundary conditions in addition to those of ideal MHD. First the component of the magnetic field normal to the fluctuating plasma-vacuum interface must vanish on both sides of the interface, and second an additional regularity condition is imposed on the linearized magnetic field at $r = 0$. For small ε, we analyze the fourth order system by the method of matched asymptotic expansions. For the special case of a theta pinch with $m = 0$ and $\Delta\cdot\underset{\sim}{v} = 0$, the solution in the turning point region is given explicitly in terms of Fresnel integrals and a related function. We show that the Alfvén wave continuum of ideal MHD is replaced by a discrete set of eigenvalues with a spacing of order ε. We consider passage to the limit of ideal MHD in terms of the initial value problem by letting $\varepsilon\to 0$ and discuss the significance of our results for Alfvén wave heating.

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HEAT TRANSPORT IN TOKAMAKS AS OBSERVED FROM SAWTOOTH OSCILLATION CHARACTERISTICS*

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We illustrate recently derived methods[1,2] of measuring heat transport by analyzing some high density Alcator discharges. The analysis is shown to provide very accurate results for $\chi(r) = 1/2(\chi_e(r) + \chi_i(r))$. The importance is stressed of τ_{ie}, the electron-ion temperature equilibration time in deciding which is the effective (electron or ion) transport mechanism. Examples are shown where transport is dominated by electrons, by ions and initially by electrons and then by ions. A survey is presented of heat transport in tokamaks using these methods.

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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.

†Visitor from Junta de Energia Nuclear, Madrid, Spain.

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ANOMALOUS SLOWING DOWN OF ALPHA PARTICLES IN TOROIDAL PLASMA*

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A systematic search for alpha driven high frequency instabilities with substantial anomalous transport consequences results in bands of modes in the frequency range $\omega_{ci} < \omega < \omega_{pi}$, with the fastest mode near ω_{pi} being mainly electrostatic. For the wave vector k such that $m = \ell = o$, $k = k_r$, to lowest order, the lack of poloidal mode structure leads to spatial detuning of the destabilizing term and an essentially unmagnetized response function.

We calculate the linear growth rate, the alpha threshold density, solve the steady state quasilinear equations for $f_{\perp\alpha}$ and $D_{\perp\alpha}$ and determine the relaxation time of perpendicular alpha energy. (The resonance does not affect the parallel energy, to leading order.) This instability provides anomalous slowing down to near thermal energy at a rate much faster than collisional, as will be shown quantitatively.

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POLOIDAL MAGNETIC FIELD FLUCTUATIONS IN TOKAMAKS*

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Elementary nonlinear tearing mode theory in two-dimensional cylindrical geometry is used to predict accurately the amplitude of the m = 2 poloidal magnetic field fluctuations (Mirnov oscillations) at the limiter of a tokamak. The input required is the electron temperature radial profile from which the safety factor profile can be inferred. The saturation amplitude of the m = 2 tearing mode is calculated from the safety factor profile using a nonlinear Δ' analysis. This gives an absolute result (no arbitrary factors) for the amplitude of the perturbation in the poloidal magnetic field everywhere and, in particular, at the limiter. An analysis of ORMAK and T-4 safety factor profiles (inferred from electron temperature profiles) gives results that are in agreement with the experimental data.

A study of a general profile shows that as a function of the limiter safety factor a maximum occurs in the Mirnov oscillations. The magnitude of the maximum increases with a decrease in temperature near the limiter.

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MAJOR DISRUPTIONS IN TOKAMAKS: T-4 AND PLT*

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In Ref. 1, we reported that according to the analysis of the reduced resistive MHD equations for highly resistive plasmas ($S_{axis} < 10^5$) with a nonlinear finite difference code, a possible mechanism for major disruptions for safety factor profiles flat in the tokamak core, is the nonlinear interaction of the m = 2/n = 1 and m = 3/n = 2 tearing modes, both of which are linearly unstable for these profiles. Specifically, employing a finite difference code we found that for S as large as 10^5 the 2/1 mode further destabilizes the 3/2 mode and other modes, particularly the 5/3. The toroidal current density is severely deformed due to the development of many magnetic islands across the tokamak cross section, and we expect a corresponding loss of heat and plasma along the ergodic field lines.

In order to confirm this result for smaller resistivity (larger S), a new code, has been constructed that uses the Fourier transform in the poloidal and toroidal directions with the number of modes retained being variable. For S_{axis} as large as 10^6 at the plasma center, the essential six-mode interaction and the rapid time scale reported in Ref. 1 has been confirmed for the PLT safety factor profile. For this value of S, the destabilization of the 3/2 takes place as the 2/1 island width grows linearly with time, i.e., as the 2/1 mode evolves in the Rutherford regime.

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

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GENERATION OF LARGE MAGNETIC ISLANDS IN THE SINGLE PITCH APPROXIMATION*

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Large $m = 2/n = 1$ magnetic islands can be produced when the current density falls fast enough near the limiter (there exists a cold layer). No flattening of the q-profile is required. The use of a new nonlinear code (RSF) that employs the Fourier transform in the poloidal and toroidal directions avoids the numerical problems associated with the saturation of large magnetic islands when a coarse poloidal grid[1] is used in the MASS code.[2] For comparable accuracy, the computer time required is in favor of RSF by a factor of 40 to 1 The results of the two codes will be compared in detail.

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

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TWO SPECIES NEUTRAL TRANSPORT MODEL*

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In a plasma consisting of two hydrogen isotopes (H and D or D and T) the neutral particle transport is described by a Boltzman equation for each neutral species. These two equations are coupled by charge exchange of the neutrals of one species with the plasma ions of the other species. This provides each neutral population with a volume source and sink term in addition to electron ionization. We have developed a code which solves for the neutral density and energy profiles in a slab geometry using simplified collision operators to describe the charge-exchange coupling. Global neutral particle and energy balances are calculated along with the energy spectrum of emerging neutrals and the resulting sputtered flux of wall impurities. The code is being used to analyze charge-exchange data from recent experiments in ISX-A in which deuterium was puffed into a hydrogen plasma. Coupled with a two-species plasma transport code, the neutral routine is also being used to investigate if an inward plasma pinch must be included in the density equation in order to reproduce the observed penetration of the puffed deuterium to the center of the hydrogen plasma.

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ENHANCED MIRROR CONFINEMENT DUE TO MHD OSCILLATIONS*

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ABSTRACT

It has been noted that primarily magnetic oscillations produce a ponderomotive potential which attracts plasma.[1] This leads to the possibility of enhancing plasma confinement by driving bulk MHD oscillations. We discuss the possibility of using this scheme to enhance plasma confinement in a mirror device. At low oscillation amplitudes one can confine the low energy ions needed for stabilization of the loss cone driven modes. At larger oscillation amplitudes the ion loss rate is reduced since ions with significant parallel velocities are confined.

In order for such a scheme to be practical, the power associated with driving this oscillation must be small. Preliminary results indicate that the small power required does not significantly add to the existing circulating power.

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Solution of a Linearly Unstable Non-Linear P.D.E. by the Inverse Scattering Method*

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ABSTRACT

A non-linear version of the Klein-Gordon Equation

$$\phi_{xx}-\phi_{tt}+i\,|\phi|^2(\phi_x-\phi_t)+\phi=0 \qquad (1)$$

has been derived by Aamodt, et al. [Phys. Rev. Lett. 39, 1660 (1977)] to describe the linear growth and saturation of the drift-cyclotron wave in mirror machines. It is shown that Eq. (1) is reducible to a linear "scattering" problem and shares the remarkable features--soliton solutions, conservation laws--of other non-linear equations that may be solved by the inverse scattering method. Numerical results are given for a localized initial perturbation and those show behavior descriptive of the ion-cyclotron bursting phenomena observed in mirror machines. Speculations are presented regarding long-time behavior of the solution.

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EQUILIBRIA FOR FIELD-REVERSING RINGS*

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ABSTRACT

I have investigated a technique for finding equilibria for field-reversing rings. The plasma is completely confined to a finite region. Finding the fields in the vacuum region requires a procedure analogous to the Wiener-Hopf technique.

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High Order Methods for Nonlinear Time Dependent MHD[†]

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With the advent of the newer computers the computation of three dimensional nonlinear MHD dynamics into the saturated state for long times is becoming a real possibility. It is therefore necessary to insure that the computational methods be as accurate and efficient as possible. This work concerns a comparison of several high order difference methods for multidimensional nonlinear time dependent MHD equations.

We present results showing fourth order difference methods to be more effective than similar second order methods. The fourth order methods require less running time and less computer storage than the second order schemes. A Fourier (spectral) method is also introduced which further reduces core storage and hence allows the computation of plasmas with higher order structure. Detailed comparisons are given for a 2-D linearized set of equations. Stability results are also presented for the 3-D nonlinear problem in both cartesian and cylindrical geometry using simple analytic equilibria*.

* Bateman, G., Hicks, H.R., Wooten, J.W.,"3-D Nonlinear Evolution of MHD Stabilities", ORNL/TM-5796, March 1977.

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† Work supported by DOE, Contract No. EY-76-C-02-3077.

Scaling and Similarity Laws for Plasma Confinement†

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Scaling laws for plasma confinement are rigorously derived from similarity considerations based on the classical diffusion equations (due to Grad and Hogan) including resistivity and heat conduction.

The confinement time τ is found to obey the scaling laws

$$\tau = \frac{\rho L^2}{k} F\left(\frac{\rho\eta}{k}, \beta\right) \tag{1}$$

where ρ, k and η are the average plasma density, heat conductivity and resistivity, respectively and L is the typical length in the device.

The use of diffusion equations suppresses Alfvén wave phenomenon and the $\sqrt{\rho}$ scaling factor associated with it. This also reduces the number of dimensionless parameters in the scaling laws from 4 (for the full MHD equations) to 2 in equation (1). The practical implication is that the scaling laws in (1) cover a wider variety of experiments than the result for the full MHD equations.

Specific results are presented by considering various functional dependences of η and k on T, B, etc. The possibility of a scaling law linear in ρ is also examined.

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Nonlinear Stability Problems on Two Time Scales†

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A general theory for treating nonlinear stability problems in dissipative plasmas is developed, based on a Two-Time Method extended to a system of partial differential equations. Assuming small dissipative effects, the first order system is identical with that for the usual linear MHD stability problem; dissipative and nonlinear effects are to appear on the slow time scale in higher order systems. For modes with finite frequencies on the fast time scale, the amplitudes are evolving on the slow time scale and are governed by a system of ordinary differential equations with coefficients depending on the Eigenfunctions of the first order system. For modes with low frequencies or small growth rates, nothing happens on the fast time scale; waves and nonlinear effects interact with dissipative effects on the slow time scale, resulting in a system of higher order derivatives. Stability related criteria on the slow time scale are obtained wherever possible. Ohmic heating and skin effects are also included.

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The Stabilizing Effects of Pressure Anisotropy†

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The influence of large pressure anisotropy on the stability of nearly cylindrical high beta plasma columns is investigated using the Guiding Center Plasma model. Weitzner[1] has shown that pressure anisotropy can be used to stabilize such a plasma column. Here, it is shown that increasing ther perpendicular pressure locally can substantially reduce growth rate of the unstable gross motion of the plasma. The reduced instability is a result of the reduction of mirroring force the charged particles feel along the magnetic field lines.

The stability analysis consists of an asymptotic expansion about a diffuse profile theta pinch, the expansion parameter being the small helical distortion of flux surfaces from that of straight cylinders. The result of the expansion is an ordinary differential equation eigenvalue problem.

The most interesting pressure anisotropy seems to be one where a species perpendicular pressure is enhanced over its parallel pressure at some radius from the center of the plasma. Modes with nodal structure greater than one become extremely localized, and the no node perturbation is stabilized. The only gross mode remaining has one node.

1. H. Weitzner, submitted to Physics of Fluids.

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† Work supported by U.S. DOE Contract No. EY-76-C-02-3077.

Effect of Current Profiles on MHD Stability Limits in Tokamaks*

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MHD kink and ballooning modes will limit the achievable β in tokamaks. Therefore, systematic numerical studies of the dependence of the critical β on the various parameters are being made. Extensive studies with the PEST code[1] on the effects of geometry, including aspect ratio and cross-section shaping, were reported previously.[2] Here we summarize our studies of the effects of changing q and q' on β. These studies indicate that this profile is the most sensitive and least understood parameter to be considered. In systems with moderate shear, β_{crit} for external kink modes decreases as q_{lim} increases for $q_o = 1$. Calculations employing a pressureless plasma outside the limiter show improvement, but with results very sensitive to the shape of q. Internal ballooning mode limitations are also sensitive to this shape.[3] With conventional current profiles β_{crit} decreases as $q_o \gtrsim 1$ is increased for fixed q_{lim} and for fixed $q_{lim} - q_o$. However, large local shear near the axis, as occurs in recent very high-β JET models,[4] appears to improve internal mode stability. We have analyzed a set of these equilibria with $\beta^* \sim 20\%$ with respect to low-n internal modes with PEST and to high-n modes with the BALLOON code. These modes are stabilized when $q_o = 1.6$ with large q' near the axis. As before, the $n = 1$ external kink mode becomes more unstable with increasing q_o.

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†On loan from Westinghouse Research and Development Center.

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EVIDENCE FOR MAGNETIC STOCHASTICITY AS THE MECHANISM FOR HEAT TRANSPORT IN ALCATOR:

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Soft x-ray spectra on Alcator indicate that the electron distribution function is significantly non-Maxwellian in the 4 to 15 keV range, and this anomaly (tail) persists at plasma densities as high as 4×10^{14} cm^{-3}. The anomaly cannot be explained by the conventional Spitzer-Harm electric-field-driven perturbation.[1] Even including the known toroidal[2] and runaway[3] corrections, the dominant contributions of these effects is odd in the velocity component along the electric field and hence does not contribute to the soft x-ray spectrum. We have investigated the effects of destroyed magnetic surfaces on the electron distribution function. It is well known that a helically resonant perturbation leads to a destruction of magnetic surfaces.[4] The effects on plasma confinement will be substantial only if there is a spectrum of perturbations, as could be produced by microinstabilities which have saturated at a modest level.[5] In the presence of such stochastic field lines the electrons can move radially, modifying the distribution function as well as producing substantial thermal transport.[6] We show that the resulting distribution function has an enhanced tail. By adjusting the level of magnetic field fluctuations, we fit the soft x-ray spectrum. The diffusion coefficient so obtained agrees with the bulk energy confinement measurements, both in absolute magnitude and in scaling with plasma density.

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PLASMA FREQUENCY RADIATION IN TOKAMAKS

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A systematic examination of emission mechanisms for electromagnetic radiation at the plasma frequency in tokamaks is given. Of the mechanisms so far considered, only that of (1) appears to account for the experimental data.[2] In (1) the emission results from the scattering of an unstable electrostatic (ES) plasma spectrum produced by runaway electrons[3] from thermal level (sound) fluctuations. This leads to (non-linear) self-absorbed radiation at the central plasma frequency, with predominantly extraordinary polarization. Enhanced but stable ES plasma waves give emission[4] by the same process but at power levels well below those seen experimentally and frequencies below the central plasma frequency (as is not seen). Emission also results from discreteness[5] but without sufficient intensity to account for the ω_{pe} line. This process may, however, explain some other features in the spectrum.

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Collisionality Dependence of the Pfirsch-Schlüter Contribution to Neoclassical Diffusion*

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The contribution to the neoclassical transport coefficients in an axisymmetric toroidal plasma which arises from the poloidal variation of the parallel friction forces is investigated in the transition between plateau and Pfirsch-Schlüter (P.S.) regimes. A coupled system of kinetic equations for the $\ell = 0, 1$ velocity harmonics of the distribution function is obtained. This system is solved using a generalized moment expansion whose closure is based on a mini-max variational procedure. Although the P.S. diffusion coefficients scale as $\alpha q^2 D_c$ in all collision frequency regimes, the magnitude of the numerical coefficient α undergoes a transition from a "collisionless" value[1] to a collisional value[2] when $\nu_s \nu_E \sim \omega_T^2$, i.e., $\epsilon^{3/2}\nu_* \sim (\nu_s/\nu_E)^{1/2} \geq 1$ (here, ν_s and ν_E are the momentum and energy exchange collision frequencies). In contrast to previous treatments utilizing a maximal variational principle[1] or a model collision operator[3], the fluxes computed here are asymptotically equal to the exact collisional values.[2] The extremum principle[1] is found to overestimate the P.S. contribution. Comparing the total neoclassical flux (P.S. and anisotropy-driven portions) with Ref. 3, it is found that the model operator method underestimates the P.S. flux. Our results are fitted to simple formulas for numerical application.

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DRIFT MODE STABILITY ANALYSIS FOR TMX

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Abstract

Drift mode stability analysis for TMX is formulated with FLR fluid equation for cross-field currents and kinetic theory for parallel currents. In the absence of resonant particle currents, a set of Hermitian differential equations are obtained for the wave field which, following Ref. 1, is described in terms of the electrostatic potential, the parallel inductive field and a purely rotational perpendicular electric field. The equations are compared with those of Berk and Dominguez. The familiar electrostatic equation for $\beta \approx 0$ is on the diagonal containing the zero beta interchange stability criterion. With beta of order unity the equations show the well-known neutral stability with respect to the self-dug magnetic well.[2] Assuming neutral MHD stability from weak field curvature and uniform rotation, the system of equations describe two potentially unstable drift modes. For $k_{||} \sim \pi/L_c$ where L_c is the length of the central cell the electron drift wave occurs with $\omega \sim \omega_{*e} S(b,\eta_i) \sim k_{||} v_A$ with a radial localization $\Delta r^2 \leq r_n \rho/\beta^{1/2}$. The lower azimuthal modes ($m \leq 5$) are weakly collisional for initial TMX parameters. Stability conditions as a function of η_i, η_e, β and T_i/T_e are developed. For flute-like modes ($k_{||}L_c \ll 1$) the ion drift wave $\omega \sim \omega_{*i} \gg k_{||}v_e$ occurs and is less localized in radius and extends to higher frequencies than the electron wave. Stability conditions for the ion wave due to the $\nabla_{\perp}B$ and bounce frequency resonance with the electrons are developed.

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