1990
SHERWOOD THEORY CONFERENCE

APRIL 23-25, 1990
WILLIAMSBURG, VIRGINIA

Wren Building, Campus of William & Mary

UNDER THE AUSPICES OF COLLEGE OF WILLIAM & MARY

1990
INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

APRIL 23-25, 1990
HILTON HOTEL AND CONFERENCE CENTER
WILLIAMSBURG, VIRGINIA

Under the auspices of

COLLEGE OF WILLIAM AND MARY
Williamsburg, Virginia

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GENERAL INFORMATION

* 270 papers were submitted, of which 15 were selected for oral and review presentation.

* The review papers will be presented in the Auditorium, Monday, Tuesday, and Wednesday mornings beginning at 8:30 a.m.

* All oral papers will be presented in the Auditorium, Monday and Tuesday mornings beginning at 9:30 a.m. Each talk will be 25 minutes in length plus 5 minutes for discussion. An overhead transparency machine and a slide projector are provided for the presentations.

* Poster sessions will be held in rooms 2, 3, and Center Lounge, Monday afternoon, Tuesday evening, and Wednesday morning.

* A banquet will be held on Monday evening at 7 p.m. in the President's Hall. Tickets may be purchased at the Registration desk.

* Refreshments will be served in Lounge A & B consisting of coffee and tea during the morning sessions; beer and soft drinks during the afternoon and evening sessions.

* A Companion's breakfast will be held on Monday morning at 9 a.m.

* Requests for special meetings should be made with Barbara Sarfaty at the Conference Registration Desk.

1990

INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

HILTON HOTEL AND CONFERENCE CENTER, WILLIAMSBURG, VIRGINIA

APRIL 23-25, 1990

SCHEDULE

<u>*REGISTRATION*</u> - *Conference Center Lobby*

Sunday, April 22, 1990 - 6 - 10 p.m.

Monday, April 23, 1990 - 7:45 a.m. - 5 p.m.

Tuesday, April 24, 1990 - 7:45 a.m. - Noon and 7 - 9 p.m.

Wednesday, April 25, 1990 - 8 - 10 a.m.

<u>*ORAL AND POSTER SESSIONS*</u>

Review and oral talks - *Auditorium*

Posters - *Rooms 2, 3, and Center Lounge*

<u>Monday, April 23, 1990</u>

Welcome - 8:20 a.m. - A.H. Boozer, Chairman

1A -Review Paper - 8:30 a.m.

1B - Oral Session - 9:30 a.m. - 12:30 p.m.

12:30 - 2 p.m. - *LUNCH BREAK*

1C - Poster Session - 2 - 4 p.m.

1D - Poster Session - 4 - 6 p.m.

7 - 9 p.m. - *BANQUET*

<u>Tuesday, April 24, 1990</u>

2A - Review Paper - 8:30 a.m.

2B - Oral Session - 9:30 a.m. - 12:30 p.m.

12:30 - 7 p.m. - *FREE TIME*

2C - Poster Session - 7 - 9 p.m.

<u>Wednesday, April 25, 1990</u>

3A - Review Paper - 8:30 a.m.

3C - Poster Session 9:30 - 11:30 a.m.

3D - Poster Session 11:30 a.m. - 1:30 p.m.

Coffee and Tea - 9:30 a.m., Monday through Wednesday

Beer and Soft drinks - 3 p.m. Monday and 7 p.m. Tuesday

1990 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE
ANNUAL CONTROLLED FUSION THEORY CONFERENCE

Hilton Hotel and Conference Center
Williamsburg, Virginia
April 23 - 25, 1990

SUNDAY REGISTRATION 6:00 - 10:00pm

MONDAY REGISTRATION 7:45am - 5:00pm

WELCOME 8:20

MONDAY MORNING 8:30 - 12:30pm

1A REVIEW SESSION
8:30am
Presiding: Chuan Liu

1A1. Review of Theory of Neoclassical and Anomalous Transport. R. Z. Sagdeev.

1B ORAL SESSION
9:30am
Presiding: Kurt Riedel

1B1. Local Dependence on Current in Tokamak Microinstabilities. W. M. Tang, G. Rewoldt, and T. S. Hahm.
1B2. Energetics of Resistive Interchange Turbulence in the RFP. D. C. Barnes.
1B3. Intense Lower-Hybrid Wave Penetration: Improved Theory and Prospects for Experimental Tests. R. H. Cohen, P. T. Bonoli, M. Porkolab, and T. D. Rognlien.
1B4. Ion Temperature Gradient Driven Turbulence in Sheared Magnetic Fields with Steep and Flat Density Profiles. S. Hamaguchi and W. Horton.
1B5. Turbulence Effects on MHD Stability. C. Litwin and S. C. Prager.
1B6. Plasma Heating by Collisionless Tearing and Reconnection: Analysis and Computation. R. W. Moses, J. M. Finn, and K. M. Ling.

LUNCH 12:30 - 2:00

MONDAY AFTERNOON 2:00 - 6:00pm

1C POSTER SESSION
2:00 - 4:00pm

1C1. Models of Inertial Range Spectra of Inhomogeneous MHD Turbulence. Y. Zhou and W. H. Matthaeus.
1C2. A Study of Filamentation Using Self-Consistent Ray-Tracing. A. J. Neil, E. R. Tracy, and A. H. Boozer.

1C3. Investigations on the Alfven-Ballooning Modes in Tokamak Discharges. Y. Z. Zhang and S. M. Mahajan.
1C4. Current Sheet Stability and the Fast Crash of Sawteeth in Tokamaks. R. G. Kleva.
1C5. Anomalous Transport in Toroidal Plasmas. A. Punjabi, A. H. Boozer, K. Burke, and K. Muytung.
1C6. A Numerical Algorithm for ICH Control of the Alpha Particle Transport in a General Geometry. K. Imre, C. S. Chang, H. Weitzner, and P. Colestock.
1C7. Effect of Neutral Particles on Ion Transport in a Tokamak. R. D. Hazeltine, P. M. Valanju, and E. R. Solano.
1C8. Scattering of Millimeter Radiation from Magnetic and Density Fluctuations in a Tokamak. G. Vahala, L. Vahala, and D. J. Sigmar.
1C9. Perturbative Transport due to Drift Wave Fluctuations. A. A. Thoul, P. L. Similon, and R. N. Sudan.
1C10. MHD Stability Analysis of High-beta JET Discharges. G. T. A. Huysmans, J. P. Goedbloed, T. C. Hender, O. J. Kwon, E. Lazzaro, and D. P. O'Brien.
1C11. Semi-Implicit Particle Simulation of Kinetic Plasma Phenomena. B. I. Cohen and T. J. Williams.
1C12. M(degree)=1 Internal Modes in High Temperature Regimes. S. Migliuolo and F. Porcelli.
1C13. Role of Fueling-Induced Instabilities in Tokamak Edge Turbulence. A. S. Ware, P. H. Diamond, D. R. Thayer, B. A. Carreras, and J.-N. Leboeuf.
1C14. Enhanced Edge Transport in Sheared Systems. D. R. Thayer, P. H. Diamond, A. S. Ware, B. A. Carreras, C. Hidalgo, J. A. Holmes, J.-N. Leboeuf, Ch. P. Ritz, and A. J. Wootton.
1C15. Analytic Solutions to the Grad-Shafranov Equation with Separatrices. F. W. Perkins.
1C16. Self-Consistent Low-Z Pellet Ablation Model in a Fusion Plasma. L. Vahala, G. Gerdin, P. Parks, and A. G. El Cashian.
1C17. Indications from the Dimensional Analysis of the L-Mode Data Base. R. J. Bickerton.
1C18. A Robust Iterative Algorithm for Computing Equilibria and Adiabatic Evolution in MHD. A. Eydeland, A. Lifschitz, J. Spruck, and B. Turkington.
1C19. 3D Simulation of the Fluid eta(sub i) Instability. J. F. Drake, P. N. Guzdar, and A. M. Dimits.
1C20. Solutions for Toroidal Magnetic Fields by way of Field-line Invariants. B. Abraham-Shrauner and H. R. Lewis.
1C21. An Approach to Aneutronic Fusion with Electrostatic Confinement. G. H. Miley, J. Nadler, Y. Gu, T. Hochberg, and O. Barnouin.
1C22. Magnetic Flux Generation and Consumption in a Single-Turn Tokamak. E. Montalvo, J. Q. Dong, R. Carrera, R. R. Khayrutdinov, F. J. Helton, and M. N. Rosenbluth.
1C23. High Field ECR Ion Sources based on EBT-stabilized Mirrors. L. Bromberg, J. Kesner, and D. Smatlak.
1C24. Simulation of the Ion Cyclotron Emission in the JET Tokamak. F. Kazeminejad, R. Bingham, J. M. Dawson, and V. K. Decyk.
1C25. Effects of Non-Boltzmann Electrons on the Plasma Potential. M. D. Carter, D. B. Batchelor, and E. F. Jaeger.
1C26. Numerical Investigation of Single Helicity RFP States. K. L. Sidikman, J. D. Callen, R. A. Nebel, and J. M. Finn.
1C27. Flux-Minimizing Curves for Area-Preserving Maps. R. L. Dewar and J. D. Meiss.
1C28. A Novel Compact Torus. J. M. Finn, P. N. Guzdar, and J. F. Drake.
1C29. Model for MARFE-detached Plasma Transition in Tokamaks. P. K. Kaw, S. Deshpande, S. Rath, and K. Avinash.
1C30. An L-H Mode Bifurcation Theory Involving Poloidal Rotation. F. L. Hinton.
1C31. MHD Computation of Feedback Stabilization of Helical Modes. E. J. Nilles, S. C. Prager, and Y. L. Ho.
1C32. Global, 1-D, Kinetic Stability for FRC Equilibria. C. Choi and P. Papanikolaou.
1C33. The Ambipolar Structure of the Reversed Field Pinch. R. A. Gerwin.
1C34. A Parallel 2D Electrostatic PIC Code for the Mark III Hypercube. R. D. Ferraro, P. C. Liewer, V. K. Decyk, and J. M. Dawson.
1C35. Anomalous Transport in the Hot Ion H-Mode. R. R. Dominguez and R. E. Waltz.
1C36. Onset of the H-Mode and Resistive MHD Stability. H. R. Strauss.
1C37. Collisional Transport in Braided Magnetic Fields. G. Laval.
1C38. Analytical Stability Boundary for Delta(prime)-Type Resistive Ballooning Modes at High Beta. J. W. Van Dam, G. Y. Fu, D. L. Holland, B. D. Fried, and A. Banos.

1C39. Turbulent MHD Relaxation with Cross helicity. W. T. Stribling and W. H. Matthaeus.
1C40. Full-Wave and Ray Tracing Studies of Ion Cyclotron Heating and Current Drive in Tokamaks. P. T. Bonoli and M. Porkolab.
1C41. Particle Simulations of Transport in a Diverted Tokamak Scrape-off Layer: The High-recycling Regime. R. J. Procassini, C. K. Birdsall, and B. I. Cohen.
1C42. Dissipation Range Spectra in Space and Laboratory Plasmas with Implications for Charged Particle Diffusion and Transport. C. W. Smith, W. H. Matthaeus, J. W. Bieber, and N. F. Ness.
1C43. Multiple Mode Conversion. D. R. Cook and A. N. Kaufman.
1C44. Equilibrium Studies Using a Two-Fluid Drift Wave Turbulence Model. J. A. Crotinger and A. E. Koniges.
1C45. Transport of Electrons in Bifurcated Tokamak Equilibria. P. Garabedian and M. Taylor.
1C46. Neoclassical Resistive MHD Equations in General Toroidal Geometry. J. Y. Kim, W. Horton, J. G. Yang, Y. H. Oh, and D. I. Choi.
1C47. Amplification of Resonant Perturbations in Tokamaks. A. H. Reiman and D. A. Monticello.
1C48. A Model of Sheath-Driven Impurity Production by ICRF Antennas. D. A. D'Ippolito, J. R. Myra, M. Bures, and J. Jacquinot.
1C49. 3-D Simulation of eta(sub i) Modes in a Sheared Magnetic Field (Slab Geometry). H. V. Wong, P. M. Lyster, and H. L. Berk.
1C50. Selective Decay and Isolated Coherent Structures. W. H. Matthaeus, W. T. Stribling, D. Martinez, S. Oughton, and D. C. Montgomery.

1D POSTER SESSION
4:00 - 6:00pm

1D1. Independent Determination of Beta(sub p) and I(sub i) for Nearly Circular Tokamaks and RFPs. S. P. Hakkarainen and J. P. Freidberg.
1D2. Vertical Stability Analysis of Highly Elongated DIII-D Discharges. A. D. Turnbull, E. A. Lazarus, F. J. Helton, and J. A. Leuer.
1D3. Alfven Gap Mode Model. R. Betti and J. P. Freidberg.
1D4. Statistical Mechanics of Coulomb Systems in Finite Space. M. Kiessling.
1D5. Fokker-Planck Modelling of the Lower-Hybrid Current Drive and its Investigation Using Cyclotron Radiation. I. Fidone, G. Giruzzi, and M. J. Marcha.
1D6. Discussion of Kink-Tearing Mode Relation. H. L. Berk, S. M. Mahajan, and Y. Z. Zhang.
1D7. Ion-Temperature-Gradient Modes in the Long Wavelength Limit. L. Chen, S. Briguglio, and F. Romanelli.
1D8. Analytic Solutions of Fringing Fields for an Ion-Bernstein Wave Antenna with Faraday Screen. V. S. Chan, S. C. Chiu, and F. W. Perkins.
1D9. Entropy Production and Variational Bounds on Fluctuations. C. Y. Wang, A. Bhattacharjee, and E. Hameiri.
1D10. Variational Principle for Vlasov Equation on a Symplectic Leaf. B. A. Shadwick, P. J. Morrison, and H. Ye.
1D11. Interaction Mechanisms in Drift Wave Turbulence. X.-H. Wang, P. H. Diamond, and F. Y. Gang.
1D12. Particle Simulation Method for Non-Circular Toroidal Plasmas Using Non-orthogonal Curvilinear Coordinate Systems. K. Umegaki, M. J. LeBrun, and T. Tajima.
1D13. Gyrokinetic Particle Simulation of Drift and Trapped Particle Modes in a Toroidal Metric. M. J. LeBrun and T. Tajima.
1D14. Particle Simulations in Toroidal Geometry. W. D. Nystrom, D. C. Barnes, M. J. LeBrun, and T. Tajima.
1D15. Fractal Dimensions of Asymptotic States in Plasmas. D. Vassiliadis, S. Sharma, and D. Papadopoulos.
1D16. Convective Modes of Drift Waves in Toroidal Plasma Systems. S. Yoshikawa and C. Z. Cheng.
1D17. Nonlinear Theory of Flat Density Ion Temperature Gradient Toroidicity Induced Trapped Electron Modes in Hot Ion H-Mode Plasmas. T. S. Hahm.
1D18. Nonlinear Dynamics of Dynamo and Quasiperiodic Relaxation in RFPs. Y. L. Ho and G. G. Craddock.
1D19. On Standard Forms for Transport Equations and Fluxes - Part II (3/2 vs. 5/2 again?). D. W. Ross.
1D20. Stochastic Magnetic Fields and Electron Heat Transport Induced by Neoclassical MHD Instabilities. D. A. Spong and B. A. Carreras.

1D21. High Frequency Surface Helicity Injection in Axisymmetric Toroids with Moving Plasma Boundaries. K. Avinash and P. K. Kaw.

1D22. Three-dimensional Visualization of the Reconnection and Tilting of a Compact Torus in the Refueling of a Tokamak. D. V. Anderson, A. A. Mirin, and D. E. Shumaker.

1D23. Self-Stability of Mercier Modes in a Heliac. C. Alejaldre, A. Varias, A. L. Fraguas, B. A. Carreras, N. Dominguez, and V. E. Lynch.

1D24. Review of Evidence for Magnetic-Turbulence-Induced Transport. R. J. Goldston.

1D25. Nonlinear Instability, Chaos, and the Three-Wave Interaction. C. S. Kueny and P. J. Morrison.

1D26. Fast Wave Current Drive Calculations for ITER using the ORION code. E. F. Jaeger, D. B. Batchelor, and M. D. Carter.

1D27. Equilibrium Beta Limits in Heliotron-E due to Magnetic Island Overlap. Y. Nakamura, M. Wakatani, C. C. Hegna, and A. Bhattacharjee.

1D28. Current Density Profile Evolution and Steady State Configurations. R. C. Englade.

1D29. The MFE Database: Content and Access. W. H. Miner, J. C. Wiley, and D. W. Ross.

1D30. Analytic Theory of Current Drive by an Exact Solution of Kinetic Equation. T. P. Khan.

1D31. An Explanation for New Cold Fusion in Metal Electrodes - A New Quantum Effect in Nuclear Fusion. W. Hongzhang.

1D32. Coherent Structures in eta(sub i)-Mode Turbulence. B.-G. Hong, F. Romanelli, and M. Ottaviani.

1D33. Variational Theory of Neutral Particle Transport. M. Calvin, R. D. Hazeltine, P. M. Valanju, and E. R. Solano.

1D34. The Exact and Drift Hamiltonian. Q. Yao, M. Guo, and A. H. Boozer.

1D35. Maximum Entropy Equilibria of a Nonneutral Guiding-Center Plasma. R. A. Smith and T. M. O'Neil.

1D36. Numerical Computations of Resistive MHD Instabilities. T. R. Harley, C. Z. Cheng, and S. C. Jardin.

1D37. Guiding Center Stochasticity in a Tokamak. K. Kupfer, A. Bers, and A. K. Ram.

1D38. Transport Simulations of TFTR Experiments to Test Theoretical Models for chi(sub e) and chi(sub i). M. H. Redi.

1D39. Particle Transport and Fueling Issues for DT Diverted Plasmas. W. A. Houlberg and M. J. Gouge.

1D40. Improved Analytic Equilibrium for a Field Reversed Configuration. L. C. Steinhauer.

1D41. Determination of the Energy Confinement Time in a Slowly Evolving Plasma. H. St. John, L. L. Lao, D. P. Schissel, and J. C. DeBoo.

1D42. Simulation of High Energy Electrons in the Reversed Field Pinch. A. G. Sgro, D. C. Barnes, and R. A. Nebel.

1D43. Radiative Decay of Grad T(sub e) Drift Wave Monopole Vortices. X. N. Su, W. Horton, and P. J. Morrison.

1D44. Saturation Dynamics and Spectrum of Trapped Particle Drift Instabilities Using 3D Gyrokinetic Simulation Models. R. D. Sydora, W. W. Lee, J. M. Dawson, and T. S. Hahm.

1D45. Minimization of Resistive Flux Loss During Current Rise. T. B. Kaiser.

1D46. Three Dimensional Field Lines in a Tokamak with a Divertor - A Chaotic Scattering Problem. Y.-T. Lau and J. M. Finn.

1D47. About Possibility of Divertor Configuration Creating in T-3M Tokamak. R. R. Khayrutdinov, V. E. Lukash, S. V. Mirnov, and V. P. Fokin.

1D48. Size and Field Scaling for Dimensionally Similar Tokamak Discharges. R. E. Waltz, M. N. Rosenbluth, and J. C. DeBoo.

1D49. Stability Properties of the ATF Torsatron During Entry to the Second Stability Region. L. A. Charlton, B. A. Carreras, J.-N. Leboeuf, and V. E. Lynch.

1D50. Relativistic Standard Map. Y.-H. Ichikawa, H. Nomura, and W. Horton.

BANQUET 7:00

TUESDAY MORNING 8:30am - 12:30pm

2A REVIEW SESSION
8:30am
Presiding: Vincent Chan

2A1. Plasmas with a Single Sign of Charge (A Review of Recent Theory and Experiment). T. M. O'Neil.

2B ORAL SESSION
9:30am
Presiding: Ron Moses

2B1. Ballooning Modes in Plasmas and in Classical Fluids. E. Hameiri and A. Lifschitz.
2B2. A Unified Physical Scaling Law for Tokamak Energy Confinement. J. P. Christiansen, J. G. Cordey, and K. Thomsen.
2B3. Tokamak to Tokamak variation and Colinearity in Scaling Laws. K. S. Riedel.
2B4. A Review of Massively Parallel Computing in the MFE Program. A. A. Mirin.
2B5. A Banana-Passing Fluid Model for Tokamak Density Profiles. R. W. Harvey and R. O. Dendy.
2B6. Caviton Correlations in Strong Langmuir Turbulence. D. Russell, D. F. DuBois, and H. A. Rose.

TUESDAY AFTERNOON 12:30 - 7:00
FREE TIME

TUESDAY EVENING 7:00 - 9:00pm

2C POSTER SESSION
7:00-9:00pm

2C1. Stability of the Gas Dynamic Trap. G. V. Stupakov and H. L. Berk.
2C2. Fluid/Kinetic Hybrid Moment Description of Plasmas via a Chapman-Enskog-Like Approach. J. P. Wang, J. D. Callen, and Z. Chang.
2C3. Trapped Particle Effects on Resistive Ballooning Modes. A. K. Sundaram and J. D. Callen.
2C4. On the Possibility of Deriving Trapped Particle Modes from Fluidlike Equations. J. D. Callen, Z. Chang, A. K. Sundaram, and J. P. Wang.
2C5. Use of a Fluid/Kinetic Hybrid Model for Including Kinetic and Collisional Effects in Fluidlike Models. Z. Chang, J. D. Callen, and J. P. Wang.
2C6. Transport Bifurcation Induced by the Poloidal Electric Field in the Scrape-off Layer. G. M. Staebler.
2C7. Fluctuation-Dissipation Theorem of a Nonthermal Magnetized Plasma and Its Application to Scattering of Electromagnetic Waves. S. C. Chiu.
2C8. Ballooning Modes in Tokamaks with Sheared Flow. F. L. Waelbroeck and L. Chen.
2C9. Field Error Correction Studies for a Reversed-Field Pinch Stabilizing Shell. D. A. Baker, M. S. Hoyt, D. W. Kerst, L. W. Mann, and C. W. Nielson.
2C10. Effect of Sheared Toroidal Plasma Flows on the Equilibrium and Stability of Tokamaks. A. Sen, A. K. Agarwal, and S. N. Bhattacharya.
2C11. Gyrokinetic Simulations in the Presence of Collisions. S. Ma, R. D. Sydora, and J. M. Dawson.
2C12. The Statistical Dynamics of Turbulent Plasma Convection. J. A. Krommes.
2C13. Localized Source Effects on Neoclassical Transport and L-H Transitions. E. R. Solano and R. D. Hazeltine.
2C14. Minimum Energy Dissipation States and Predictions of the MHD Configurations in Fusion Confinement Devices. X. Shan, H. Chen, and D. C. Montgomery.

2C15. Statistical Modeling of Drift Wave Turbulence. A. E. Koniges, J. A. Crotinger, W. P. Dannevik, P. A. Amala, and P. H. Diamond.
2C16. Singular and Nonsingular Plasma Equations for the Collisionless Sheath. X. D. Zhang and R. D. Hazeltine.
2C17. Symmetries and Global Transport Equations. B. Coppi and F. Pegoraro.
2C18. The Neoclassical Transport of Toroidal Momentum in Tokamaks. A. A. Ware.
2C19. Resistive Stability at High-beta. A. Y. Aydemir and A. D. Beklemishev.
2C20. Influence of Radial Electric Fields on Turbulent Fluctuations in Toroidal Plasma. G. S. Lee.
2C21. Observation of Temperature Dependent Transport in TFTR. P. C. Efthimion, D. K. Mansfield, S. C. Cowley, R. J. Goldston, B. C. Stratton, E. Synakowski, M. C. Zarnstorff, D. McCune, R. Wieland, P. H. Diamond, H. Biglari, A. Bhattacharjee, and C. C. Hegna.
2C22. Spectral Methods for Compressible Flows. M. Hossain, W. H. Matthaeus, and S. Ghosh.
2C23. Self-Consistent Plasma Effects on Magnetic Field Ripple. M. S. Chance and G. S-Y. Chiu.
2C24. Fast Wave Current Drive Calculations Using the Geometrical Optics Code RAYS. R. C. Goldfinger and D. B. Batchelor.
2C25. Massive Parallelization of Fluid Turbulence Simulations in Tokamaks. G. D. Kerbel and R. E. Waltz.
2C26. Particle Simulation on the NCUBE Concurrent Multiprocessor. R. W. Huff and J. M. Dawson.
2C27. Thermal alpha-particle Transport Study. S. C. Hu and G. H. Miley.
2C28. Basics of Tearing Modes. T. H. Jensen.
2C29. Generalized EDQNM Closure Applied to a Two-field Fluid Model of the Ion Temperature Gradient Mode. J. C. Bowman, J. A. Krommes, M. Ottaviani, and H. E. Mynick.
2C30. Bifurcation of Poloidal Equilibrium Flows and Transport Fluxes in Tokamak Plasmas with Impurities. C. T. Hsu.
2C31. Studies of Feedback Stabilization of Axisymmetric Modes in Deformable Tokamak Plasmas. D. J. Ward, S. C. Jardin, and C. Z. Cheng.
2C32. Canonical Hamiltonian Guiding Center Variables. R. B. White.
2C33. Scenarios of ICRH in Phaedrus-T. P. Moroz, R. Majeski, and N. Hershkowitz.
2C34. Fractal Transport in Stochastic Magnetic Fields. M. B. Isichenko.
2C35. Turbulence Saturation and Poloidal Flow Velocity. B. A. Carreras, V. E. Lynch, and L. Garcia.
2C36. Conservation Properties of a Gyrokinetic Fokker-Planck Collision Operator. A. Brizard.
2C37. Passive Control of the Plasma Vertical Instability in a Single-Turn Tokamak. J. Q. Dong, E. Montalvo, R. Carrera, R. R. Khayrutdinov, and M. N. Rosenbluth.
2C38. Simulations Using the Multi-Mode Transport Model. G. Bateman.
2C39. Gyroresonance Crossing, Quasilinear Diffusion and Conservation Laws in Axisymmetric Toroidal Plasma. H. Ye and A. N. Kaufman.
2C40. A 1-D Transport Code for the RFP based on a Theoretical Turbulence Model. D. D. Schnack, Z. Mikic, G. G. Craddock, Y. L. Ho, and J. B. McBride.
2C41. Collapse of Drift Wave Vortices from Magnetic Shear. W. Horton, X. N. Su, and P. J. Morrison.
2C42. Wave Kinetic Theory. A. H. Boozer.
2C43. Connections in a Hierarchy of MHD Modes. A. A. Blank and M. E. Kress.
2C44. Tearing Mode Stability in a Tokamak. M. S. Chu, M. Klasky, and J. M. Greene.
2C45. Non-Existence of Quasi-Helically Symmetric Equilibria. D. A. Garren and A. H. Boozer.
2C46. Suggested Tokamak Parameter Regimes. F. J. Helton, J. M. Greene, and M. Klasky.
2C47. Magnetohydrostatic Equilibria and Force-Free Fields. N. A. Salingaros.
2C48. On the Importance of Neutrals in Ion Thermal Transport Studies. P. M. Valanju, R. Bravenec, A. Ouroua, and R. D. Bengtson.
2C49. Radiative Condensation Instability in a Tokamak Edge Plasma. R. Singh, C. V. S. Rao, K. Avinash, S. Deshpande, and P. K. Kaw.
2C50. Nonlienar Interaction of Tearing Modes in the Presence of Equilibrium Shear Flow. X. L. Chen and P. J. Morrison.

WEDNESDAY MORNING 8:30 – 1:30pm

3A REVIEW SESSION
8:30am
Presiding: Ron Cohen

3A1. Theoretical Problems of Direct Relevance to ITER. W. M. Nevins and ITER. Team..

3C POSTER SESSION
9:30-11:30am

3C1. Collisionless Two-Fluid Model of Curvature-Driven Ion-Temperature Gradient Transport. J. P. Mondt and J. Weiland.
3C2. Effect of Tokamak Electrostatic Edge Fluctuations on Orbits and Transport. C. L. Hedrick and J.-N. Leboeuf.
3C3. Gyrokinetic Simulation of Energetic Particle Effects on Tokamak Stability. K. T. Tsang and C. Z. Cheng.
3C4. Modeling of Fluctuations at the Edge of the TEXT Tokamak. J.-N. Leboeuf, B. A. Carreras, J. A. Holmes, D. K. Lee, V. E. Lynch, Ch. P. Ritz, A. J. Wootton, P. H. Diamond, A. S. Ware, and D. R. Thayer.
3C5. Fluidlike Studies of the Sheath and Presheath Regions of a Plasma. B. J. Lee and J. D. Callen.
3C6. Turbulence and Transport Simulations for Experimental Parameters Using the Kinetic Delta f Particle Algorithm. M. Kotschenreuther.
3C7. Operational Conditions for an Ignition Experiment. R. Carrera, E. Montalvo, and M. N. Rosenbluth.
3C8. Conversion of 3-D VMEC Code Output into 2-D STEP Code Input for Stability Studies of General Configurations. J. L. Johnson, G. Rewoldt, Y. Nakamura, M. Wakatani, and K. Ichiguchi.
3C9. The Axial Mode Revisited. W. S. Lawson.
3C10. Suppression of Magnetic Islands by Energetic Ions in Toroidal Plasmas. C. C. Hegna and A. Bhattacharjee.
3C11. Dissipative Structure in Plasma Turbulence. S. Bujarbarua.
3C12. Fluid Models for Landau Damping and the Ion Temperature Gradient Instability. G. W. Hammett and F. W. Perkins.
3C13. One-and-a-Quarter Dimensional Transport in the Presence of the Collisional Velocity-Space Particle Loss in Field-Reversed Configurations. P.-R. Chiang and M.-Y. Hsiao.
3C14. Electrical Conductivity in Tokamaks Modified by Electrostatic Trapping in the Applied Electric Field. C. S. Chang.
3C15. Scattering and Localizability of ECH Power in CIT. G. R. Smith.
3C16. The Physics of Nonneutral Plasmas in Traps. L. Turner.
3C17. Numerical Reconstruction of Equilibria From Measurements of Tokamaks Operating at the Poloidal Beta Equilibrium Limit. M. E. Mauel.
3C18. A Portable Implementation of the Reduced MHD Equations. J. C. Wiley and A. Y. Aydemir.
3C19. The Stabilization of the l=2 Instability in Hollow Nonneutral Plasmas by Means of Oscillating Electric Fields. R. L. Spencer.
3C20. Anomalous Transport of Fast Alphas. D. J. Sigmar and C. T. Hsu.
3C21. Enhanced Transport and MHD Stability kin Tokamaks. R. H. Weening and A. H. Boozer.
3C22. A Deterministic Particle Method for Collisional Equations. G. Russo.
3C23. Nonlinear Pressure Driven Resistive Modes in Tokamaks. W. Park, D. A. Monticello, E. Fredrickson, B. Grek, and K. McGuire.
3C24. Renormalization Group Analysis of Alfven Turbulence in Reduced MHD. D. W. Longcope and R. N. Sudan.
3C25. Nonlinear Ion Mixing Mode Particle Flux in Electron Trapping Regimes. P. W. Terry.
3C26. Time Dependent Effects and the Current Ramp Phase in D-T Ignition. L. E. Sugiyama and M. Nassi.

3C27. Current Flow in the B2 Edge-Plasma Code. M. E. Rensink, J. L. Milovich, and T. D. Rognlien.
3C28. Cross-Field Drifts and Periodic Boundary Conditions in the B2 Edge-Plasma Code. T. D. Rognlien, R. H. Cohen, J. L. Milovich, and M. E. Rensink.
3C29. Complete Fluid Equations for Singular MHD Modes in Toroidal Plasmas. A. H. Glasser.
3C30. Microstability of Hot Electrons Generated by Intense Microwave Pulses in the Microwave Tokamak Experiment. Y. Matsuda and G. R. Smith.
3C31. Development of Godunov Methods for MHD Flows with Shocks. Z. Mikic, D. R. Thayer, and D. D. Schnack.
3C32. Plasma Turbulence Calculations on the Intel RX Hypercube. V. E. Lynch, B. A. Carreras, J. B. Drake, and J.-N. Leboeuf.
3C33. Current Drive via Helicity Waves in Arbitrary Geometry. R. R. Mett and J. A. Tataronis.
3C34. Kinetic Electron Modelling of Plasma Near the Neutralizer Plate in a Tokamak Divertor. T. W. Johnston, Z. Abou-Assaleh, J. P. Matte, R. Marchand, and K. J. Parbhakar.
3C35. Computer Simulation of Transport Driven Current in Tokamaks. W. J. Nunan, R. D. Sydora, and J. M. Dawson.
3C36. Non-Local Efficiency in Wave Driven Tokamaks. J. M. Rax and D. Moreau.
3C37. Coupled g-mode/resistivity Gradient Driven Turbulence in the Edge of the Reversed Field Pinch. G. G. Craddock, P. W. Terry, and K. L. Sidikman.
3C38. Resistive Tearing Mode Instability with Shear Flow. L. Ofman, X. L. Chen, P. J. Morrison, and R. S. Steinolfson.
3C39. Burn Threshold for Fusion Plasmas with Helium Accumulation. B. D. Fried, R. J. Taylor, and G. J. Morales.
3C40. Wave-kinetic Formulation of Incoherent Linear Mode Conversion. E. R. Tracy and A. N. Kaufman.
3C41. The m=1 Internal Kink Mode in a Rotating Tokamak Plasma with Anisotropic Pressure. H. J. De Blank.
3C42. High-Density Z-Pinches from a Computational Viewpoint. I. R. Lindemuth.
3C43. Curvature Drift Modifications of Magnetic Field Maps for Runaway Electrons in the TEXT EML Configuration. P. J. Catto, J. R. Myra, and J. B. Taylor.
3C44. "Universal" Nonlinear Drift-wave Turbulence. B. D. Scott.
3C45. Particle Dynamics in the Neighborhood of a Magnetic Null. J. W. Larson and E. R. Tracy.
3C46. Exact Nonlinear Solutions for Drift-RMHD Dynamics. M. G. Prahovic, R. D. Hazeltine, and P. J. Morrison.
3C47. Iterative Semi-Implicit Scheme. V. Varadarajan and G. H. Miley.
3C48. Electron Cyclotron Heating Studies in the Compact Ignition Tokamak. M. Porkolab, P. T. Bonoli, R. C. Englade, and A. H. Kritz.
3C49. Numerical Study of the Spectrum for Nonneutral Plasma Equilibria. S. N. Rasband and R. L. Spencer.
3C50. Hamiltonian Chaos and Anomalous Transport. G. M. Zaslavsky and R. Z. Sagdeev.

3D POSTER SESSION
11:30-1:30pm

3D1. Simulation of a 2-D Model of Dissipative Convective Cell Turbulence. D. E. Newman, P. W. Terry, and P. H. Diamond.
3D2. Analysis of Alpha Physics Aspects of the IGNITEX Experiment. Z. Guo, R. Carrera, G. Y. Fu, L. M. Hively, G. H. Miley, E. Montalvo, M. N. Rosenbluth, S. Tamor, J. W. Van Dam, and H. Xiao.
3D3. Theory of the Tokamak Beta(a)B/I Limit. J. J. Ramos.
3D4. Calculation of 3-D Equilibria with Islands for the IMS Stellarator. O. Betancourt, D. Anderson, and J. Talmadge.
3D5. Numerical Model of Multifield Plasma Turbulence Based on DIA Closure. W. P. Dannevik, P. A. Amala, A. E. Koniges, J. A. Crotinger, and P. H. Diamond.
3D6. Stabilization of Drift-Tearing Modes and Breaking Constant-Psi. F. Porcelli, S. Migliuolo, and F. Pegoraro.
3D7. A Boundary Integral Method for Computing Minimum Energy States. G. J. Marklin and D. C. Barnes.
3D8. Resistive Modes in Tokamaks. W. Kerner, J. P. Goedbloed, S. Poedts, and E. Schwarz.
3D9. FRC Vlasov-Fluid Global Stability Calculations Using MHD Eigenfunctions as Basis Functions. J. L. Staudenmeier, M.-Y. Hsiao, D. C. Barnes, and H. R. Lewis.

3D10. Recent Results in Numerical Modeling of the RACE Experiment. J. L. Eddleman, J. H. Hammer, C. W. Hartman, and B. G. Logan.
3D11. 3-D MHD with Two-Fluid Corrections for the Reversed Field Pinches. R. A. Nebel, L. Turner, R. Veerasingam, and P. Sheehey.
3D12. Multifractal Properties of Passive Scalars Convected by Chaotic Fluid Flows. T. M. Antonsen, E. Ott, and F. Varosi.
3D13. An Approach to Time Series Data Analysis of Dissipative Driven Tokamaks. D. Dobrott, J. A. Thomson, S. Auerbach, J. Kadtke, and H. Abarbanel.
3D14. 1 1/2-D Transport and Stability Calculations. R. Fitzpatrick, C. G. Gimblett, R. J. Hastie, and T. J. Martin.
3D15. Numerical Simulation of Ion Temperature Gradient Driven Modes in the Presence of Ion-Ion Collisions. X. Q. Xu and M. N. Rosenbluth.
3D16. Propagation of Ion-Bernstein Waves in Toroidal Plasmas. A. K. Ram and A. Bers.
3D17. Spontaneous Poloidal Spin-up of Tokamaks and Enhanced Confinement. A. B. Hassam, T. M. Antonsen, J. F. Drake, and C. S. Liu.
3D18. Finite Bloch-shift Effects on Drift Wave Stability in Toroidal Plasmas. F. Zonca and L. Chen.
3D19. Reciprocity Relations and the Mode Conversion-Absorption Equation with an Inhomogeneous Source Term. D. G. Swanson and S. Cho.
3D20. Absorption and Emission of Plasma Waves at High Harmonics of the Ion Cyclotron Frequency. S. Cho and D. G. Swanson.
3D21. CQL3D Calculations of the Radial Profiles of Lower Hybrid Current Drive. M. G. McCoy and R. W. Harvey.
3D22. Resistive MHD Stability Analysis of TFTR Supershots. M. H. Hughes and M. W. Phillips.
3D23. Hydrogen Recycling with Resonance Line Reabsorption. R. Marchand and J. Lauzon.
3D24. Plasma Parameters and Scaling Laws for Mirrortron Ion Accelerators. R. F. Post.
3D25. Direct Conversion of Muon Catalyzed Fusion Energy. T. Tajima, S. Eliezer, and R. M. Kulsrud.
3D26. Symplectic Integration of Guiding-Center Orbits. J. R. Cary and J. A. Rome.
3D27. Kinetic Effects on Ion Temperature Gradient Driven Turbulence. A. M. Dimits, J. F. Drake, and W. W. Lee.
3D28. The Role of the Internal Kink Mode in Experiments. J. Manickam, D. Roberts, R. Kaita, F. Levinton, M. Okabayashi, and R. B. White.
3D29. Numerical Determination and Experimental Measurement of Vacuum Fields for 3-D ICRH Antenna Configurations. K. Ko, W. Grossmann, A. Drobot, P. Colestock, G. Greene, J. Hosea, J. Stevens, R. Wilson, T. Tanaka, R. Majeski, and N. Hershkowitz.
3D30. Time Evolution of Tokamaks Based on the Braginskii Model. H. Weitzner.
3D31. Gyrokinetic Particle Simulation of Gradient-Driven Micro-instabilities. J. V. W. Reynders, R. Santoro, and W. W. Lee.
3D32. Transition to H-Mode Behavior Produced by Radial Currents. H. Ramachandran, B. D. Fried, and G. J. Morales.
3D33. Effect of Velocity Fields on Saturated Island Widths. N. Pomphrey and A. H. Reiman.
3D34. Stabilization of Ballooning Modes by Energetic Ions in TFTR Supershots. A. Bhattacharjee, X.-H. Wang, G. W. Hammett, K. McGuire, and R. L. Miller.
3D35. Gyrokinetic Particle Simulations of Electrostatic Plasma Turbulence. T. J. Williams, B. I. Cohen, R. H. Cohen, L. L. LoDestro, W. M. Nevins, W. A. Newcomb, and R. D. Sydora.
3D36. Sheath-Plasma Modes and Anomalous Loading in IBW Experiments. J. R. Myra, D. A. D'Ippolito, D. W. Forslund, and J. U. Brackbill.
3D37. Nonlinear Saturation of Ideal Interchange Modes. A. D. Beklemishev.
3D38. Tight Aspect Ratio Tokamaks. A. Sykes, J. Hugill, D. C. Robinson, T. N. Todd, H. F. Turner, P. K. Browning, G. Cunningham, S. J. Gee, D. Kitson, and M. G. Rusbridge.
3D39. 2-D Gyroviscous MHD - Stability Analysis. R. Acevedo and P. J. Morrison.
3D40. Dissipative Trapped Electron Drift Wave Turbulence. N. Dominguez, B. A. Carreras, V. E. Lynch, L. A. Charlton, J.-N. Leboeuf, L. Garcia, and P. H. Diamond.
3D41. Poloidal Plasma Rotation in Tokamaks. K. C. Shaing and R. D. Hazeltine.
3D42. Reciprocity Relations for Coupled Rational Surfaces. A. Pletzer, R. L. Dewar, and J. M. Greene.

3D43. Ballooning Modes on Finite Length Field Lines. M. Mond and E. Hameiri.
3D44. Effects of Non-uniform Rotation on the Ion Temperature Gradient and Trapped Particle Instabilities. A. K. Sen and S. Migliuolo.
3D45. Energetic Particles and MHD Modes. C. Z. Cheng.
3D46. MHD Simulations of the Direct Energy Extraction from Rotating FRC Plasmas. J. Cobb, T. Tajima, and R. Lovelace.
3D47. Three Dimensional MHD Computation of Global Toroidal Modes. F. Cap.
3D48. Electron Transport from Drift-Wave Turbulence Driven by Temperature Gradient. C.-B. Kim, W. Horton, and B.-G. Hong.
3D49. Current Drive Scenario in a Flexible Heliac. F. Castejon and C. Alejaldre.

Review of Theory of Neoclassical and Anomalous Transport

R. Z. Sagdeev

Department of Physics and Astronomy
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Local Dependence on Current in Tokamak Microinstabilities*

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Although the presence of low frequency drift type microinstabilities dependent on trapped particles and ion temperature gradient effects would be consistent with a number of important confinement trends observed in tokamak plasmas, conventional estimates for these instabilities cannot account for the strong current (I_p) and/or q-scaling frequently found in empirically deduced global energy confinement times. The present study focuses on physics features, ignored in simpler estimates, which might introduce an appreciable local dependence on the current. Numerical results from a comprehensive kinetic stability code[1] indicate that the local growth rate is found to scale roughly as $\gamma \propto q^\alpha$, with $\alpha \sim 0.7$ to 1.5 for values of $q(a)$ between 2 and 7. For larger $q(a)$ (*i.e.*, lower current values), this dependence becomes less apparent. Such behavior can be explained in part by the fact that as $q(a)$ (and the associated local rq'/q) increases, the equilibrium value for the trapped-particle orbit-averaged magnetic drifts becomes increasingly unfavorable for $q(a)$ values up to 7 or so. This can significantly influence both the resonant (precession resonance) and non-resonant (interchange type) destabilization processes asssociated with such drifts. In addition, favorable transit-ion Landau damping effects are also enhanced for lower values of $q(a)$. With respect to nonlinear effects, a weak turbulence analysis of the magnetic-drift-resonance-driven trapped electron modes indicates a much stronger q-scaling than typical $\gamma/k_\perp^2$ estimates.

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

[1]G. Rewoldt, W. M. Tang, and R. J. Hastie, Phys. Fluids **30**, 807 (1987).

Energetics of Resistive Interchange Turbulence in the RFP *

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The power flow via resistive interchange ("g-mode") turbulence is examined. The turbulent state is modeled as an ensemble of quasi-steady, field-aligned vortices. For a given vortex, the power flow from liberation of energy from the mean pressure gradient, to dissipation via resistivity and viscosity is easily estimated. The balance between these energy sources and sinks to the turbulent flow determines all the statistical properties of the turbulence.

In particular, these estimates are applied to resistive interchange turbulence near the reversal surface of a RFP configuration. (This is the RFP confinement region, where the thermodynamic gradients are maximum.) The saturated amplitudes of the velocity and magnetic fields, their spectra in toroidal mode number (the direction normal to both the mean field and the mean pressure gradient), and the resulting transport via convection and Rechester-Rosenbluth electron conduction along the stochastic **B** field are derived. The estimated power flow is also shown to be consistent with anomalous equipartition of T_i with T_e observed in RFP discharges. A nonnegligible dynamo contribution is also found to be associated with the turbulent state.

A comparison of these results with previous work is made, and the application to other magnetized plasma turbulence problems is discussed briefly.

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* Work conducted under the auspices of the USDOE

Intense Lower-Hybrid Wave Penetration: Improved Theory and Prospects for Experimental Tests*

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Application of lower-hybrid power in short, intense pulses enhances penetration in reactor-grade plasmas by saturating the power absorbed through Landau damping.[1] We report here on a number of advances in the theoretical description as well as an investigation of the feasibility of a near-term experimental test. Extensions of the theoretical description include an improved absorption calculation which is now consistently relativistic, includes electromagnetic effects (a minor correction), and quantitatively includes the effect of finite repetition rate (an important beneficial effect). Our earlier study of parametric instabilities has been upgraded to include a more accurate criterion for depletion of the intense pump; the results indicate that the marginally tolerable decay-product growth rate is increased more than three-fold from earlier estimates. We have also developed a partial description of pump depletion suitable for incorporation in a ray-tracing code; initial results will be presented. We have examined ponderomotive-force density reduction at the edge, and find it to be acceptably small. Filamentation instability is under investigation; preliminary results will be presented. Finally, we have examined an alternate regime of longer pulse length (comparable to the plateau relaxation time) and lower peak power, and identified advantages and disadvantages relative to the shorter-pulse regime. Experimental tests could be done on various tokamaks; we examine in particular prospects for a test on MTX. We find that, given a suitable spectrum, for 200 MW multi-ns pulses and long ($\sim$ 25 cm) launchers, or 10 MW, 100 μs pulses, the power will penetrate significantly further in MTX than weaker (continuously applied) power.

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

† Permanent Address: Massachusetts Institute of Technology, Cambridge, MA 02139

1 R. H. Cohen, P. T. Bonoli, M. Porkolab and T. D. Rognlien, in "Radio-Frequency Power in Plasmas, Eighth Topical Conference" (AIP Conference Proceedings **190**, New York, 1989), 126.

SHERWOOD THEORY MEETING 1990

Ion Temperature Gradient Driven Turbulence in Sheared Magnetic Fields with Steep and Flat Density Profiles*

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The ion temperature gradient driven mode or η_i-mode[1] turbulence is reinvestigated analytically and numerically based on two component compressible fluid equations with the polarization drift velocity and adiabatic electrons. It is shown that the anomalous ion heat conductivity χ_i variation with magnetic shear $s = L_n/L_s$ scales as

$$\chi_i \;=\; g\left(\frac{\rho_s}{L_n}\right)\left(\frac{cT_i}{eB}\right)(\eta_i - \eta_{i,c})\exp(-\alpha s)$$

with $g \simeq O(1)$, $q_i = L_n/L_{T_i}$ and $\alpha \simeq 5$ when η_i is near its critical value $\eta_{i,c}$. In the limit of flat density profile ($\eta_i \gg \eta_{ic}$), the parameter α scales as $\alpha \propto \beta/K$ and we obtain

$$\chi_i \;=\; g\left(\frac{\rho_s}{L_{T_i}}\right)\left(\frac{cT_i}{eB}\right)\exp\left(-\frac{\beta s}{K}\right)$$

with $\beta \simeq 4$. Our new results show that the anomalous transport and the saturation level of the η_i-mode are reduced by magnetic shear, qualitatively consistent with previously obtained results.[1,2] The effects of nonlinear FLR terms and the role of finite poloidal shear flows will be briefly discussed.

1. W. Horton, R. D. Estes, and D. Biskamp, Plasma Physics **22**, 663 (1980).

2. W. Horton, D. I. Choi, and W. M. Tang, Phys. Fluids **24**, 1077 (1981).

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

TURBULENCE EFFECTS ON MHD STABILITY

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S.C. Prager
University of Wisconsin, Madison, WI

In manly experimental situations the plasma may be in a turbulent steady state. The turbulence may be characterized by high frequency modes, driven by velocity-space effects, or by low frequency modes, driven by inhomogeneities. The presence of fluctuations can alter significantly the plasma stability to MHD modes. Its effect can be described by time-averaged, ponderomotive and magnetization forces which modify both the momentum balance and Ohm's law. We apply the calculations to three examples of experimental interest. First, the Alfven-ion cyclotron instablity can stabilize the ideal internal kink. This mechanism may be responsible for the monstor sawtooth stability in JET. Second, the alpha particle loss-cone instability stabilizes the flute mode in the reactor parameter regime. Finally, we consider the effect of low frequency magnetic turbulence on the resistive internal kink mode. We explore the possiblity that this turbulence is responsible for the observation in several tokamaks that the sawtooth oscillations are not well-described by the Kadomtsev picture of total reconnection.

Supported by U.S. Department of Energy

Plasma Heating by Collisionless Tearing and Reconnection: Analysis and Computation*

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This paper presents simple analytic and numerical models of the collisionless magnetic tearing and reconnection process. The magnetic field is taken to be a vacuum quadrupole field in the *x-y* plane. The electric field, $\mathbf{E}_0$, is uniform in the *z*-direction to provide continuous reconnection along the *z*-axis. Plasma is introduced on a magnetic flux surface. Charged particle orbits are computed precisely as trajectories cross the separatrix to reach an outgoing flux surface, at the same distance from the origin as the starting surface.

It is found that the magnetic moments of charged particles passing through the unmagnetized region around the origin are randomized. There is a consequent net change of particle kinetic energy for these trajectories. Analytic modeling predicts that particles which start out monoenergetically and encounter the unmagnetized region will acquire a distribution function $f \propto \exp(-mv^2/2T_f)$. The derived result for the final effective temperature is $T_f = (3/4)qE_0x_f$ where m and q are particle mass and charge respectively, and x_f is the impact parameter of the endpoint flux surface. This expression is in agreement to ~ 25% with the statistical results of the particle tracking code for a normalized electric field[1] ranging over three orders of magnitude. The full distribution function consists of an essentially unperturbed component corresponding to particles that miss the unmagnetized region, plus the Maxwellian tail with width T_f described above. The computed current density in the unmagnetized region allows one to state the range of plasma density for which this vacuum field model is valid.

The particle beams observed in Ref. 1 are not seen in this simulation because the present computation begins and ends well outside of the unmagnetized region. The distribution function of the small number of highly accelerated particles appears to have a "fractal" like dependence on trajectory initial conditions characteristic of elastic scattering.

By following the evolution of monoenergetic components of the input distribution function, it is thus possible to describe plasma thermalization during tearing and reconnection in analytic terms verified by numerical orbit computations. These results provide a substantial simplification in the understanding of particle acceleration and heating produced by magnetic tearing and reconnection.

1. G. R. Burkhart, J. F. Drake, and J. Chen, "Magnetic Reconnection in Collisionless Plasmas: Prescribed Fields", to be published in J. Geophys. Res.

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* Work performed under the auspices of the USDOE
+ Laboratory for Plasma Research, University of Maryland

Models of Inertial Range Spectra of Inhomogeneous MHD Turbulence

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Recently developed transport theories for small scale inhomogeneous MHD fluctuations explicitly treat convection, expansion and other interactions with large scale gradients, while seperating nonlinear effects associated with triple correlations of the fluctuations. These transport theories may be applicable to laboratory plasma physics and space physics. To close these models, approximations for the nonlinear terms are needed, since exact treatment of the triple correlations is tantamount to a full solution of the turbulence problem, which is unavailable even for the case of homogeneous turbulence. We present a framework, based on turbulence theory, to develop approximations for the local turbulence effects that are required in transport models. Two approaches are given, based on, first, Kolmogoroff-style dimensional analysis, and second, including a unified approach to the Kolmogoroff and Kraichnan spectral theories, the inclusion of cross helicity, and a discussion of nonlinearities associated with the energy difference spectrum. We plan to implement these models to interplanetary MHD fluctuations in solar wind.

Abstract Submitted for the 1990 Sherwood Theory Meeting.

A Study of Filamentation Using Self-Consistent Ray-Tracing.

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A 2-dimensional numerical simulation of the wave-kinetic model of laser-plasma interactions introduced by Tracy and Boozer[1], is being developed. By deriving the relevant equations of motion from an action principle, the model self-consistently couples the laser to the plasma. The primary advantages over conventional ray-tracing are: the energy density of the wave is easily computed anywhere in space and time, ponderomotive effects are automatically included and the evolution of the light field is governed by a kinetic equation rather than a wave equation. We will discuss applications to the study of laser filamentation, specifically the model is well suited to the study of various *optical smoothing* techniques (e.g. *Induced Spatial Incoherence* and *Random Phase Screen* etc.) which are designed to suppress the filamentation instability.

[1] E.R. Tracy and A.H. Boozer, Physics Letters A, Vol. 139 No. 7, 1989, p 318-326.

Work Supported by the Navel Research Laboratory (Laser Plasma Branch) grant # N00014-89-K-2026.

Investigations on the Alfvén-Ballooning Modes in Tokamak Discharges*

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A kinetic eigenmode equation is derived in the Lorentzian electron conductivity model neglecting trapped particle and ion compressibility effect, but keeping toroidal drifts. This equation has three interesting limits: (1) In slab geometry it becomes the drift Alfvén equation, (2) Resistive ballooning equation when ion Larmor radius are small, and (3) Collisionless kinetic ballooning equation when resistivity is neglected. Using appropriate boundary conditions, the eigenmode equation is solved for the physically interesting parameter regime, to study the effects that are not included in the previous studies; i.e., toroidal effects on the drift Alfvén waves, ion Larmor radius and ion magnetic drift resonance on the resistive ballooning modes, and resistivity effects on the collisionless kinetic ballooning modes.

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

CURRENT SHEET STABILITY AND THE FAST CRASH OF SAWTEETH IN TOKAMAKS

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The crash of the central temperature during sawteeth in tokamaks is believed to be a consequence of the growth of a $q = 1$ tearing mode. As the $q = 1$ mode grows, the magnetic field lines are reconnected in a narrow current sheet at the X-point on a Sweet-Parker hybrid timescale $(\tau_A\tau_r)^{1/2}$, where the resistive time $\tau_r = 4\pi a^2/\eta c^2$ and the Alfvén time $\tau_A = R/c_A$. In a hot tokamak like TFTR where the Lundquist number $S = \tau_r/\tau_A \sim 10^9$, the reconnection time $(\tau_A\tau_r)^{1/2}$ based on the classical resistivity η is much too long to account for the observed fast crash of sawteeth. However, the formation of a narrow current sheet at the X-point may give rise to instabilities which broaden the sheet and alter the rate of reconnection.

The stability of a narrow current sheet embedded in a sheared magnetic field to short wavelength microtearing modes is examined. The stability of the sheet is shown to depend crucially on the sign of $I_\ell/k_{||}'$, where I_ℓ is the line current in the sheet and $k_{||}' \equiv dk_{||}(x)/dx$ is the rate of change of the parallel wavenumber in the direction of the inhomogeneity, as well as on three important characteristic lengths: Δr, the distance between the center of the current sheet and the resonant surface of the mode; the width σ_s of the sheet; and the resonant layer width w_r of the mode. When $I_\ell/k_{||}'$ is positive, the current sheet can be unstable only if $\Delta r < \frac{1}{2}\max(\sigma_s, w_r)$; otherwise the sheet is stable. Conversely, when $I_\ell/k_{||}'$ is negative the sheet can be unstable only if $\Delta r > \frac{1}{2}\max(\sigma_s, w_r)$.

The analysis is applied to the narrow current sheet formed at the X-point of the $q = 1$ mode. It is shown that the current sheet is unstable only if the width σ_s of the sheet is less than a critical width σ_{sc} given by $\sigma_{sc}/a \cong |I_s/I_0|(a/r_1)(4/q_a)$, where I_s/I_0 is the ratio of the current I_s in the sheet to the total current I_0, r_1 is the radius of the $q = 1$ surface, "a" is the minor radius, and q_a is the safety factor at the edge of the plasma. The magnitude of the current in the sheet I_s is a function of the central safety factor $q(0)$; $|I_s|$ increases as $q(0)$ decreases below unity. The width σ_s of the sheet is a function of the temperature; the sheet narrows as the plasma becomes hotter and the resistivity decreases. As a consequence, there is a critical value of the Lundquist number S_c above which the sheet is unstable. For typical TFTR parameters and $q(0) = 0.9$, the critical width $\sigma_{sc} \cong 5\rho_i$, where ρ_i is the ion gyroradius, and the critical Lundquist number $S_c \cong 10^6$. The current sheet generated in a hot tokamak like TFTR where $S \sim 10^9$ is much narrower than the critical width σ_{sc}. As a result, the sheet is unstable to a broad spectrum of short wavelength modes with $m, n > 100$, where m and n are the poloidal and toroidal mode numbers, respectively. These modes grow rapidly with a growth time of the order of one microsecond, much less than the sawtooth crash time of $50 - 100\mu sec$. This short wavelength turbulence will likely broaden the sheet to the marginally stable width σ_{sc}, with a large effective resistivity given by $S_c \sim 10^6$, and thereby increase the rate of reconnection of magnetic field lines by the $q = 1$ mode, resulting in a fast crash.

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ANOMALOUS TRANSPORT IN TOROIDAL PLASMAS

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We have developed a Monte Carlo method to estimate the transport of different groups of particles for plasmas in toroidal geometries. This method can determine the important transport mechanisms driving the anomalous transport by comparing the numerical results with the experimental data. The important groups of particles whose transport can be estimated by this method include runaway electrons, thermal electrons, both passing and trapped diagnostic beam ions etc. The three basic mechanisms driving the anomalous transport are: spatial variation of magnetic field strength, spatial variation of electrostatic potential within the flux surfaces, and the loss of flux surfaces. The equation of motion are obtained from the drift hamiltonian. The equations of motion are developed in the canonical and in the non-canonical, practical co-ordinates as well. The effects of collisions are represented by appropriate stochastic changes in the constants of motion at each time-step. Here we present the results of application of this method to three cases: superathermal alphas in the rippled field of tokamaks, motion in the magnetic turbulence of tokapole II, and transport in the stochastic fields of ZT40.
This work is supported by DOE OFE and ORAU HBCU program.

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A Numerical Algorithm for ICH Control of the Alpha Particle Transport in a General Geometry*

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ABSTRACT

Control of medium energy alpha particle transport by ion cyclotron range of frequency waves have been introduced in Ref.1. However, the validity of Ref. 1 was confined to plasmas with large aspect ratios, circular cross sectional flux surfaces with cos θ — type RF power variation in the poloidal angle θ. In the present work we present a numerical algorithm to evaluate the alpha particle flux without making any of the previous approximations on the flux-surface geometry, and on the RF power deposition profile. Application of the present formalism to ITER is discussed.

1 - C.S. Chang, P. Colestock, K. Imre and H. Weitzner, *Control of Alpha Particle Transport by Spatially Inhomogeneous Ion Cyclotron Resonance Heating*, to appear in Fusion Technology.

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Effect of Neutral Particles on Ion Transport in a Tokamak*

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In 1974, Sigmar and Clarke[1] noted that charge exchange collisions provide a momentum sink for ions, and therefore affect the ion radial particle flux. That work took into effect the non-Maxwellian (neoclassical) ion distribution while treating the impurities as Maxwellian. We use a short charge-exchange mean-free-path theory[2] for the neutrals to analyze related effects stemming from the non-Maxwellian part of the neutral distribution. It is found that (i) The effect on ion radial particle transport is small, and correctly given by previous work.[1] (ii) The effect on ion rotation is simple (but not entirely trivial, depending upon short charge-exchange mean-free-path): one replaces, in the ion diamagnetic drift, the ion pressure by the sum of the ion and impurity pressures; the same change enters the perpendicular plasma current. (iii) The effect on the ion heat flux is potentially important in the tokamak edge region: the new heat flux resulting from charge-exchange, Q_x, is related to neoclassical ion heat flux by the ratio

$$Q_x/Q_{\rm NC} \sim (n_n/n_i)(\nu_x/\nu_c)(\lambda_x/\rho_p)^2(R/r)^{1/2}$$

where $n_n(n_i)$ is the neutral (ion) density, $\nu_x(\nu_c)$ is the charge exchange (ion-ion collision) frequency, λ_x is the charge exchange mean free path, ρ_p is the ion poloidal gyroradius, and R/r is the inverse aspect ratio. Mainly because $\lambda_x \gg \rho_p$, the ratio need not be small. Furthermore we find that the inverted neutral density gradient will cause an apparent inward convection of ion energy in the edge region.

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Scattering of Millimeter Radiation from Magnetic and Density Fluctuations in a Tokamak

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To include effects of both plasma and magnetic inhomogeneities it is necessary to resort to some form of ray tracing analysis. To leading order, one obtains information on the propagation path of the millimeter radiation through the toroidal plasma. At the next order, one considers wave energy densities and obtains information on the scattering function $S(\mathbf{k},\omega)$. Here, we extend the work of Bonoli & Ott [1] to include scattering from both magnetic and density fluctuations. Using the random phase approximation and weak plasma turbulence, a wave kinetic equation is derived assuming a cold inhomogeneous plasma background with thermal effects included in the calculation of the various wave damping mechanisms. The resulting wave kinetic equation is solved by extending the Monte Carlo code of Bonoli to incorporate scattering from magnetic fluctuations.
Preliminary results will be presented on the Bretz [2] idea of detecting magnetic fluctuations from the mode conversion of O → X mode. Moreover, this theory can incorporate the effects of magnetic shear and be used as an alpha particle diagnostic. In particular, alpha-driven Alfven fluctuations can be considered and yield information on the levels of these fluctuations in future tokamaks.

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Perturbative transport due to drift wave fluctuations

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We study the anomalous electron transport due to drift-wave turbulence in tokamaks.

The incremental fluxes of particles and heat due to perturbations in the plasma gradients are obtained from the renormalized response function, using the perturbative method developed in ref.(1), which extends the results of quasilinear theory. The transport coefficients obtained in this analysis employ the ambient fluctuation spectra obtained from experimental data.

We compare our results with the quasilinear theory and with the available experimental results (ref.(2)). In particular, the TEXT tokamak furnishes fluctuation spectra, particle diffusion coefficients and heat diffusivities.

We emphasize the importance of the magnetic flutter contribution to heat tranport. The transport due to trapped electrons and the influence of ion non-linearities are also discussed.

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MHD STABILITY ANALYSIS OF HIGH-ß JET DISCHARGES

by

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ABSTRACT

Recent discharges in JET have come very close to the theoretical ß-limit (=2.8 I(MA)/a(m) B(T)). Several codes have been used to study the ideal ballooning and low-n stability of these discharges. For ballooning stability the HBT, ERATO and BALLOON codes have been used, the results being in good agreement. Typically for these high-ß discharges the electron pressure (and ion temperature) profiles have a triangular shape. For a range of discharges with triangular pressure profiles an $n = \infty$ ballooning analysis of the experimental reconstructed equilibria, shows marginal stability over the central 50% of the discharge - in some cases the core region is ballooning unstable. Occasionally high-ß discharges have a much broader, and even in some cases, a slightly hollow pressure profile; ballooning analysis of these shots shows them to approach the ballooning limit only locally on the outside of the plasma.

In some discharges very large (>10G) n= 1,2 or 3 modes seem to cause the ß to collapse. To study these low-n modes the toroidal resistive stability code FAR has been used. It is found that the computed n=1 flux surface distortions when the central-q has low shear and is just above unity, matches very well the tomographic SXR reconstructions for a pellet shot where a large n=1 mode is present. Also it is found for low central shear q-profiles (q_0= 0.95) that there are narrow bands (in q_0) for which the n=2,3... modes are unstable. These modes are the so called infernal modes [1], which remain unstable for beta's well below the ideal ballooning threshold. These low-n stability results seem to correlate well with the experimental observations of low-n high-ß activity.

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Semi-Implicit Particle Simulation of Kinetic Plasma Phenomena*

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This paper presents recent progress in improving the efficiency of particle simulations of kinetic plasma phenomena when there are disparate time scales. The direct implicit and implicit moment methods have proven successful in removing unwanted high-frequency phenomena and allowing use of large time steps in simulations of slowly evolving phenomena such as plasma transport.[1] We have extended these methods by adapting the semi-implicit integration method introduced by Harned and Kerner[2] for MHD simulations to a class of particle simulation models. There is a congruency between our new method and a simplified form of the direct implicit method. We present a description of a model algorithm and a stability analysis showing that the product of the time step and the highest normal mode frequency can much exceed unity.

In circumstances where the transit time of a species is much shorter than the characteristic time scale on which the fields vary, smaller time steps have been used for the particle advance than in the field solve; and the particle source quantities have been averaged before use in the field equation to reduce statistical requirements. This has been successfully implemented in the orbit averaging method.[3] It was later shown that orbit averaging could be combined with implicitness to achieve stability for large time steps in the field solve for particular algorithms.[4] Recently we have derived a new semi-implicit, orbit-averaged algorithm that relaxes the time-step constraints set by the highest-frequency normal mode in the system. Algorithms and stability analyses are presented for standard electrostatic particle simulation and gyrokinetic models. Some considerations on accuracy and residual constraints are also given. We have demonstrated explicit subcycled and orbit-averaged algorithms in a two-dimensional gyrokinetic code, which have dramatically improved the efficiency of the code to study drift-wave transport in tokamaks. We are implementing a semi-implicit, orbit-averaged, gyrokinetic code.

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$M^0 = 1$ INTERNAL MODES IN HIGH TEMPERATURE REGIMES

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As present experiments (e.g., JET) reach the multi-keV regime of plasma temperatures, models for the stability of $m^0 = 1$ internal modes must be improved to account for kinetic effects due to the ions and electrons. In these regimes, as well as in those relevant to planned ignition experiments such as Ignitor, standard two-fluid theory [1] is inadequate: the gyral radius of the plasma ions, ρ_i, becomes a finite fraction of the scaled radius of the singular surface, $\epsilon_\eta^{1/3} r_0$. Here r_0 is the radius where $q(r) = rB_\varsigma/RB_\theta = 1$ and $\epsilon_\eta = \eta c^2 \tau_H / 4\pi r_0^2$ is a measure of the electrical resistivity. As a consequence finite Larmor radius (FLR) effects must be taken into account. These effects are known [2] to be destabilizing in that they establish a minimum value for the thickness of the singular layer about $r = r_0$, where reconnection can occur: $\delta/r_0 = max(\rho_i/r_0, \lambda_H)$ where λ_H is the ideal MHD stability parameter. Also, in regimes where $\lambda_H < \rho_i/r_0$, FLR acts to raise the mode frequency thereby lessening the stabilizing effect of finite diamagnetic ion frequency (ω_{*i}).

We have generalized the kinetic model of Ref. [2], including the stabilizing effects of ion viscosity through a particle and momentum conserving Krook collision operator. For low values of FLR and ion viscosity effects (i.e., compared to λ_H and in the regime where the ideal mode is stable, $\lambda_H < \omega_{*i}\tau_H/2$), the normalized eigenfrequency of the internal $m^0 = 1$ resistive kink, $\lambda = -i\omega\tau_H$ becomes :

$$\lambda = i\frac{\lambda_H^2}{\lambda_i} + \frac{5\epsilon_\eta}{2\lambda_i^2} - \frac{\rho_i^2\lambda_\nu}{4\lambda_H^2}\left[\frac{\lambda_i^2\lambda_\nu^2 + 3\lambda_H^4}{\left(\lambda_i\lambda_\nu + \lambda_h^2\right)^2} - \frac{3}{4}\right] + \frac{i\rho_i^2}{4\lambda_i}\left[\frac{3}{4} - \frac{\lambda_i^2\lambda_\nu^2}{\left(\lambda_i\lambda_\nu + \lambda_H^2\right)^2}\right]$$

which clearly shows the stabilization of the FLR enhanced resistive mode when $\lambda_\nu \equiv \nu_i\tau_H$ is large enough to overcome the effect of finite electrical resistivity.

We amplify this study by numerically exploring regions in parameter space (e.g., $\lambda_H \to 0$ and/or $\rho_i/\epsilon_\eta^{1/3} r_0 > 1$) where analytic perturbation techniques are inappropriate. In this manner, we are able to rather accurately predict regimes where ignition experiments (e.g., Ignitor) will be able to operate without incurring sawtooth crashes.

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Role of Fueling-Induced Instabilities in Tokamak Edge Turbulence

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The linear and nonlinear physics of fueling-induced instabilities and turbulence is discussed in detail. Attention is focussed on thermally driven drift waves (TDDW), destabilized by thermal instability, and ionization driven drift waves (IDDW), destabilized by particle sources.

TDDW result from the coupling of drift wave oscillations to radiative instability. Since in a sheared magnetic field, parallel pressure balance occurs only for $x > |\omega| / k'_{\|} Cs = (Ti/Te)^{1/2} x_i$, i.e. at the 'tail' of the eigenfunction. Thus TDDW are driven by thermal instability, alone. A two-field ($\tilde{T}$, $\tilde{\phi}$) model, useful for analytical studies, and a four-field ($\tilde{T}$, $\tilde{\phi}$, $\tilde{n}$, $\tilde{V}_{\|}$) model of TDDW have been developed. Results indicate that the mode frequency is set by ω_{*Te}, and stability and saturation are determined by the competition between thermal instability drive and (turbulent) diffusivity enhanced thermal conduction. Saturation levels and scalings for $e\tilde{\phi}/T$, $\tilde{T}/T$ and $\tilde{n}/n$ have been determined. The results from the study of TDDW will be compared to recent fluctuation measurements from the ATF stellarator. In this regard, it should be noted that TDDW persists in the absence of current, unlike radiative-rippling modes.

IDDW results from the coupling of particle sources to drift waves. IDDW can be expected to exist in the region of neutral penetration and ionization near the edge, and is a natural candidate, since $\tilde{n}/n$ is generally large in regions of strong ionization. Moreover, since ionization drive appears to lower order in $\omega/\chi k^2_{\|}$ than does gradient drive, IDDW are insensitive to η_e-stabilization and thus can drive an inward pinch. Two-field ($\tilde{n}$, $\tilde{\phi}$) and four-field ($\tilde{n}$, $\tilde{\phi}$, $\tilde{T}_e$, $\tilde{V}_{\|}$) models have been developed, and linear theory studies for local models and in toroidal geometry have undertaken. As edge turbulence is generally along wavelength, nonlinear studies have focussed on the interaction of long wavelength, toroidal waves. Simple considerations suggest energy transfer to small scales (unlike the traditional scenario, appropriate for $k_{\perp} \rho \sim 1$) may occur. The theoretical model will be discussed and results will be discussed.

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Enhanced Edge Transport in Sheared Systems*

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We present results from our theory of radiation and ionization enhanced fluctuation induced edge turbulent transport. Our presentation will include current work on the thermally driven drift-rippling mode system. In the past, our thermally driven convective cell edge turbulent theory has enjoyed numerous successes; good qualitative agreement was demonstrated in comparison with impurity gas-puffing experiments on TEXT[1], and recent quantitative agreement was demonstrated through 3D fluid simulations[2]. However, our analysis has surfaced a serious restriction on the impurity radiation drive[3,4] which typically consists of the thermal instability as well as the condensation instability. In particular, for fusion systems with sheared magnetic fields, it is pointed out that the impurity radiative drive might not be as robust as originally thought due to the question of validity of the pressure balance assumption. In the original work on the thermally driven model, the parallel pressure balance assumption ($\delta P = 0 \rightarrow \delta n / n_0 = - \delta T / T_0$) led to the "robust" condensation enhancement (dependent on the magnitude of the radiation rate) in addition to the usual "fickle" radiative instability (dependent on the gradient of the radiation rate with respect to temperature). However, in sheared systems this is only marginally valid out on the tail of the eigenmode. Briefly, the requirement of pressure balance ($\omega, \gamma < k_{\parallel} c_s$), in a sheared magnetic field ($k_{\parallel} = k_{\parallel}' x$), implies that this constraint is valid only in the extreme radial extent of the eigenmode ($x > (T_i / T_e)^{1/2} x_i$). As a result of this observation, it was necessary to analyze the thermally driven systems, which are enhanced by the primitive radiative instability (where $\gamma_R \propto dI_Z / dT$), without using a direct pressure balance relation (where $\tilde{n}$ and $\tilde{T}$ are independently calculated). The thermally driven drift-rippling mode system for a reduced model of fluctuations consists of three coupled renormalized equations for density fluctuations ($\tilde{n}$), temperature fluctuations ($\tilde{T}$), and parallel velocity fluctuations ($\tilde{v}_{\parallel}$). We present theoretical results for the edge fluctuations (potential, density, and temperature) and the resultant transport coefficients versus radius. We also compare these results with 3D simulations conducted at ORNL and with experiments conducted on TEXT and ATF.

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Analytic Solutions to the Grad - Shafranov Equation With Separatrices

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Experiments have shown that plasma with separatrices have important properties associated with the separatrix vicinity, in particular the H-mode transition. Investigations of microinstabilities, etc. in the separatrix region must begin with an appropriate equilibrium. Force-free solutions to the Grad-Shafanov equation with $I^2 = I_o^2 + \lambda^2\psi^2$ can be obtained via separation of variables in cylindrical geometry. Superpostion of two solutions, one independant of z and another with $\psi = R\ Y_1(\alpha R)\cos(kz)$ (where $\alpha^2 = \lambda^2 - k^2$ and Y_1 is a linear combination of Bessel functions) can yield separatrices which occur in a region of zero current density. These solutions will be presented.

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SELF-CONSISTENT LOW-Z PELLET ABLATION MODEL IN A FUSION PLASMA

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The hydrogen pellet ablation model of Felber et. al. [1] is extended to the case of low-Z solid pellets. As in the Felber case, the ablation cloud is assumed to expand spherically into a background fusion plasma. The heat flux source to the pellet comes predominantly from the hot Maxwellian plasma electrons that stream towards the pellet along the magnetic field lines. Unlike the case for the hydrogen pellet, the much higher sublimation energies of the low-Z pellets require a more accurate representation of the phase transition occurring at the pellet surface. These conditions have been determined by Parks et. al. [2]. As in the hydrogen pellet case, the radial transport equations exhibit a singularity inside the Mach 1 radius and it is convenient to normalize variables with respect to their values at this singular surface. One integrates the transport equations in towards the pellet surface which is found iteratively as the solution of an eigenvalue problem under solid/gas phase transition boundary conditions. These conditions are considerably different from those for a hydrogen pellet where one can take the heat flux at the surface and the surface temperature to be zero [because of the very low hydrogen sublimation energy]. Once the pellet surface and its recession speed are determined, one integrates the fluid equations out to large r, taking into account the higher order ionization states of the low-Z ablantant. The results of this 1D radial model will be compared to the simplified thermodynamic model of Parks et. al. [2] developed for low-Z pellets.

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SHERWOOD THEORY MEETING 1990

INDICATIONS FROM THE DIMENSIONAL ANALYSIS OF THE L-MODE DATA BASE*

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Multiple linear regression has been applied to the L-mode data base to relate the suitably normalized energy confinement time to one or more of the dimensionless, Kadomtsev variables $\beta(nT/B^2)$, $G(T/B^2L^2)$, $C(n/T^{3/2}B)$ and $D(T/nL^2)$. These represent respectively the plasma beta, the ratio of gyro radius to size, the ratio of collision and gyro frequencies, and the ratio of Debye distance to size. Geometric variables such as the safety factor q, the aspect ratio R/a and the elongation k are also included.

The results show that the data base can be equally well-fitted in terms of β, G and C as by an unconstrained parameter fit. A surprisingly good fit can be obtained by retaining only β and the geometric variables. This corresponds to the ideal MHD model of plasma. Retaining β and the combination (GC^2) corresponds to the resistive MHD model. This improves the fit somewhat, giving a scaling in which

$$\tau_\varepsilon/\tau_A \propto \beta^{-1.7} S^{0.2}$$

where τ_A is the Alfven transit time and S the magnetic Reynolds number. This is a much weaker dependence on S than is given by existing resistive MHD models.

A relatively poor fit is obtained if only G is retained, corresponding to the collisionless low β-model and hence to drift-waves, gyro-reduced Bohm, etc. In particular, from the unconstrained fit the indices qualifying the power and density dependence of τ_ε do not have the correct relationship for this G only case.

These results must be described as indications rather than conclusions for a number of reasons. Global confinement data clearly encompasses the effects of the central saw-toothing zone, the intermediate zone and the plasma-wall zone where different plasma phenomena may prevail. The analysis assumes that profiles of temperature, density, particle and energy sources are similar for otherwise similar discharges in the data base. The data base itself is flawed in that the multi-parameter space is not filled with uniform density. For convenience a power law relationship between variables is assumed.

Nevertheless the indication is that the dominant mechanism determining confinement is resistive MHD rather than of drift wave type. By analogy with viscosity in fluid turbulence, it seems that resistive dissipation is essential but not important.

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A Robust Iterative Algorithm for Computing Equilibria and Adiabatic Evolution in MHD

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We develop a variational approach to two-dimensional equilibrium and adiabatic evolution problems. The method is designed to treat problems formulated in terms of conserved quantities related to q and β profiles, with either fixed or free boundary conditions. Alternatively, a variant of the method applied to standard equilibrium problems formulated with prescribed pressure and current profiles. We characterize the plasma equilibrium at a given instant of time as an energy minimizer subject to a finite family of constraints derived from the conserved quantities associated with the governing MHD equations. At a minimizer the functional dependence of toroidal current on poloidal flux in the corresponding Grad-Shafranov equation is determined along with the solution by its Lagrange multipliers. This approach allows us to consider a wide class of problems in a very natural manner. The algorithm used to generate minimizers is based upon a technique of linearization of the given constraint family at each iteration. This construction is shown to guarantee the convergence of the iterates from an arbitrary initial guess. The general method is implemented in two cases of practical interest to demonstrate its effectiveness: (a) computation of a family of flux conserving tokamaks; (b) investigation of the adiabatic compression of a plasma configuration.

3D SIMULATION OF THE FLUID η_i INSTABILITY

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We have developed a three dimensional code for the study of long wavelength η_i modes in a tokomak plasma. The code is explicit with fourth order accuracy for spatial differencing and second order accuracy for the temporal differencing. The code solves three coupled equations for density, temperature and parallel momentum. The electrons are assumed to be adiabatic and the equilibrium density is prescribed.

An extensive investigation of thermal transport in a heated slab without magnetic shear has been completed and preliminary results with magnetic shear have been obtained. In the absence of magnetic shear, the transport is a function of the single parameter $\alpha = a^2/qR\rho_i$, where qR is the periodicity length along $\mathbf{B}$, a is the minor radius and ρ_i is the ion gyroradius. For $\alpha \sim 1$ the system evolves to a coherent state with a single large "streamer" which is localized both along and across the magnetic field. For $\alpha \gg 1$, the system evolves to a turbulent state in which multiple streamers are generated at short wavelength and then coalesce. In a sheared magnetic field the system remains rather coherent even for α large. Moreover, magnetic shear does not appear to inhibit the formation of large scale streamers. The scaling of the cross field thermal transport with α and the magnetic shear will be presented.

* Work supported by DOE.

Solutions for Toroidal Magnetic Fields by way of Field-line Invariants,
B. Abraham-Shrauner, Dept. of Electrical Engineering, Washington University, St. Louis, MO 63130 and H. R. Lewis, Los Alamos National Laboratory, Los Alamos NM 87545. The general formalism[1,2] for the representation of any magnetic field with toroidal topology in terms of field-line invariants is applied to several special cases. The formalism starts with Boozer's form of magnetic fields and associates the magnetic field with a time-dependent Hamiltonian system which has one degree of freedom. The field-line invariants are found from the canonically conjugate invariants $I(q,p,t)$ for the Hamiltonian.

Previous solutions[2] for vacuum magnetic fields found from a Hamiltonian quadratic in the toroidal flux and valid in the large-aspect-ratio approximation have been extended. For a straight cylinder as the limit of the large-aspect-ratio approximation the Hamiltonian may become the axial component of the vector potential multiplied by the radius of the poloidal axis under certain conditions. This axial component of the vector potential obeys Laplace's equation in circular coordinates. The relation of these solutions to the previous solutions is discussed.

The application of the general formalism to force-free magnetic fields has produced preliminary results. The current density is equal to the magnetic field multiplied by a constant factor. Part of the magnetic field depends sinusoidally on the toroidal angle function and other differences from the vacuum magnetic field case are noted.

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An Approach to Aneutronic Fusion with Electrostatic Confinement

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Inertial electrostatic confinement[1] of a fusion plasma is brought about by the injection of electrons into a spherical, high voltage, highly transparent anode. The electron current circulating around the anode creates a negative space charge in the center of the sphere, forming a virtual cathode. Ions injected into the potential well are trapped and in an analogous fashion form a virtual anode. This attracts electrons forming a second virtual cathode, and so on. The result is a small dense fusion plasma in the center of the sphere which undergoes high fusion rates. This concept is under experimental study at Illinois. One motivation is the potential for burning advanced fuels such as D-^{3}He and p-^{11}B.

Calculations of operation with advanced fuels are presented. The reacting ions in the high density core are shown to have a highly non-Maxwellian energy distribution, approaching a broadened beam-beam distribution. A narrow distribution is most favorable for these fuels. Broadening occurs by ion-ion collisions, electron drag and angular momentum effects. The dependence on these factors is examined.

Results indicate that favorable Q-values are obtained even with p-^{11}B under optimized conditions with potential wells of less than 500 kV. This appears attainable provided a stable configuration can be maintained. Some potential instabilities are discussed.

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Magnetic Flux Generation and Consumption in a Single-Turn Tokamak*

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A single-turn coil tokamak is a tokamak confinement system that provides maximum field generation, magnetic flux coupling, and current induction capability. A device of that kind has been proposed by Rosenbluth, Weldon, and Woodson as a means to realize a self-sustained fusion reaction along the lines of Coppi's idea for a compact thermonuclear experiment. Because of the massive structure surrounding the plasma column the plasma current coupling to the structural eddy current needs is significant. Our initial analysis considers an air-core tokamak system. Requirements for internal poloidal field system operation are evaluated for infinitely resistive structural boundaries (GAEQ-GA). Magnetic flux consumption is well approximated by the Shafranov's expression. Eddy current equilibrium coupling is numerically studied by a finite elements MHD method (PROTEUS-NET). Magnetic flux generation and consumption throughout the discharge is evaluated. Results depend on the distribution of resistive sheams in the toroidal field structure. The limit situations of vacuum and superconducting structures are considered. The computational feedback between plasma equilibrium and induction calculations in the global electromagnetic system of a single-turn-coil tokamak experiment is analyzed.

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High Field ECR ion sources based on EBT-stabilized Mirrors†

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Increasing the magnetic field and the working frequency has been proposed as a method to improve the output from high-Z ECR-driven ion sources.[1] High frequency and field allows operation at high values of electron density, since the maximum density scales as $n_e \sim \omega^2$. As the working frequency is increased, so is the value of the magnetic field. In order to optimize the current of highly charged states, it is necessary to operate with a stable plasma. In the past, the plasma stability has been obtained by operating with a minimum-B geometry. The minimum-B is obtained by using quadrupole or hexapole fields on top of the axisymmetric mirror field. The production of the minimum-B geometry becomes difficult as the value of the field is increased, making the use of high frequency unattractive.

We are looking at the possibility of using an EBT-stabilized mirror in order to avoid the need of multipole fields. If it were possible to use axisymmetric fields, scaling of ECR ion sources to high freqencies (140 GHz and beyond) would be straight forward using gyrotrons. The conflicting requirements of relatively high background pressure for ring stability and low pressure to avoid charge exchange of the high-Z ions will be addressed. We will explore several schemes for electron and/or plasma injection to alleviate the relatively-high background pressure requirement for ring stability.

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† Work supported by USDOE.

[1] See, for example, R. Geller, *et al.*,, International Conference on Ion Sources, University of California, Berkeley, July 1989

Simulation of the ion cyclotron emission in the JET Tokamak

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Ion cyclotron harmonic emission can form a powerful diagnostic technique for the study of the neutral beam injection as well as alpha paricle fusion products. Here we use a $2\frac{1}{2}$ dimensional computer model with kinetic ions and massless fluid electrons to simulate neutral beam as well as fusion product experiments. For the neutral beam case the code is generalized to include interaction of a background plasma with a gradually ionizing gas of a different species which has a relative drift speed with respect to the background plasma. Waves and instabilities are then studied; after using a powerful numerical technique (subtraction) to single out the effect of the neutral beam particles on the wave spectrum, steady growth of the various modes have been observed and the most unstable modes determined. Furthermore sharp peaks in the power spectra at the various integral as well as half integral ion cyclotron harmonics for all the wave modes have been observed. In the case of fusion product modeling, we simulated the case in which a very small fraction of the plasma was comprised of the fusion products and also observed sharp power spectrum peaks at the cyclotron and the half cyclotron harmonics. These could well explain recent experimental results from the JET facility (Phys. Rev. Letters vol. 60 p33 Jan 1988) in which strong emission lines close to the ion cyclotron harmonic frequencies were observed upon injection of neutral beams as well as when significant numbers of fusion products were produced. Thus, these results may help with a theoretical understanding of the experimentally observed phenomenon.

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EFFECTS OF NON-BOLTZMANN ELECTRONS ON THE PLASMA POTENTIAL*

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The heating of the electrons in a plasma by RF fields results in an electron distribution function that can be highly non-Maxwellian. The response of these heated electrons can lead to a substantial enhancement of the total potential drop over that obtained by arbitrarily choosing a single temperature parameter to describe the electron distribution in a traditional Boltzmann approximation. Estimates for the floating potential of a plasma that is excited by electromotive RF electric fields parallel to a strong static magnetic field have been made using a Fermi acceleration heating model in the absence of Coulomb collisions. The results of using this non-Maxwellian distribution function for estimates of the static potential show that the total potential drop is proportional to the RF oscillation energy and the square root of the ion to electron mass ratio. Numerical solutions to Poisson's equation are also presented for both Boltzmann and non-Boltzmann electrons.

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Numerical Investigation of Single Helicity RFP States

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Numerical solution of the MHD equations with an imposed helical symmetry reveals the existence of helical states with edge reversal of the toroidal field. These states exhibit the following properties:

(1) They exist in a steady state.

(2) The toroidal field is reversed for all values of poloidal angle, at the plasma edge.

(3) $\langle B_z \rangle$ and $\langle \eta \mathbf{J} \cdot \mathbf{B} \rangle$ reverse at the same point.

(4) They are well–described by a quasi–static approximation; that is, there is a separation of space and time variables.

Such states could prove to be desirable in that they provide the stabilizing influence of a reversed toroidal field while maintaining a set of flux surfaces as a transport barrier. To this end, the extent to which such states are accessible in three dimensions was investigated. The results show that their appearance depends on both the initial conditions and the size of the dissipation in the equations. Some evidence of a bifurcation between a "normal" multi–helicity state and a single–helicity state can be observed as the initial conditions and dissipation are changed.

If the imposition of a single–mode initial condition does not lead to the formation a single–helicity state, it is possible that it can influence the growth of modes of different helicities. The extent to which this occurs, and affects the wandering of field lines, will be explored.

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Flux-Minimizing Curves for Area-Preserving Maps

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In several areas of plasma physics we would like well defined approximate constants of the motion at all points in phase space in order to set up improved canonical coordinates with the approximate constants as new momenta. Examples are the oscillation-center theory of particle motion in a nonintegrable potential, such as a turbulent wave spectrum, and the problem of generating magnetic coordinates in a 3D MHD equilibrium code when the constraint of assuming nested surfaces is relaxed. Dewar[1] has suggested that surfaces which minimize the mean square flux over the phase space would form optimal surfaces on which to make the new momenta constant, but nothing is known of the existence and uniqueness of such minima. Furthermore, the global integration over the Hamiltonian phase space made implementation difficult.

As a test problem for a new *Lagrangian* optimization principle we have investigated a mean-square-flux minimization principle for area-preserving twist maps. The mean absolute value of the flux through partial barriers containing action minimizing/minimax pairs of periodic or quasiperiodic orbits (cantori) has been extensively studied[2] in these maps, and it has been found that this flux is smaller through cantori than through neighboring periodic orbits. However, the absolute value norm does not lead to a unique partial barrier since it is the same for all partial barriers containing a given pair of of periodic or quasiperiodic orbits.

In the present study we do not constrain prospective barriers to contain orbits, but simply specify a pair of curves, one an image of the other under forward iteration of the twist map. This is done by specifying the rotational circle map relating the position coordinates of points mapped from one curve to the other. We show that a mean-square-flux minimizing circle map contains at least two monotone orbits. Presumably these are the action minimizing and minimax orbits.[2]

Results of numerical experiments aimed at investigating the existence and uniqueness question, and the validity of approximate solutions, using circle maps conjugate to rigid rotations will be presented.

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A NOVEL COMPACT TORUS

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Conventional compact Tori like spheromaks and FRC's are subject to violent tilt and shift instabilities. For spheromaks the tilt mode is stabilized by a closely fitting coil. However, as it decays resistivity it moves away from the proximity of the coil and is then subject to the tilt instability. In this paper we present a novel compact torus which is topologically an inside-out spheromak. This configuration has open field lines linked both inside and outside of the torus. The flux on the inside forces it up against the vicinity of the outside wall. However the last closed flux surface is insulated from the wall by open field lines provided by external coils. The advantages of this compact plasma are (a) existence of a natural divertor, (b) stability to the tilt and shift modes even when it resistively decays, and (c) possibility of D.C. helicity injection on the open field lines through the center. Taylor state analysis and 2D MHD simulations of formation using a modified MS scheme[1] will be presented.

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MODEL FOR MARFE-DETACHED PLASMA TRANSITION IN TOKAMAKS

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We present a model nonlinear calculation for the saturated state of the radiative condensation instability believed to be responsible for the MARFE phenomenon in tokamaks. After making some simplifying assumptions on the heat transport coefficients, the problem has been reduced to a well known nonlinear two dimensional equilibrium equation, for which exact solutions are known. This solution has interesting features similar to the MARFE-Detached Plasma Transition in tokamaks. We have also solved the heat balance equation with temperature dependent transport coefficients. Qualitatively the solution displays similar behaviour. Details will be presented in the paper.

An L–H Mode Bifurcation Theory Involving Poloidal Rotation

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Shear in the poloidal rotation near the edge of a tokamak plasma is expected to affect the ion thermal conductivity, because it affects the ambient edge turbulence, according to Biglari *et al.* [1]. It is assumed here that the ion thermal conductivity can be expressed as the sum of the neoclassical expression and a turbulent contribution, which is given by an *ad hoc* formula suggested by the results of Biglari *et al.* That is, the turbulent thermal conductivity is assumed to decrease with increasing poloidal rotation shear, and to be independent of its sign. It is also assumed here that the poloidal rotation is given by the standard neoclassical expression, proportional to the ion temperature gradient, where the coefficient of proportionality is a function of the ion collisionality, and therefore of the ion temperature. Taking the poloidal rotation shear to be due primarily to the variation of this proportionality coefficient, near the plasma edge, leads to a nonlinear dependence of the ion thermal conductivity on the ion temperature gradient. The resulting expression for the ion heat flux across the plasma edge, as a function of the temperature gradient, has the shape of a typical bifurcation curve, and shows a jump in the edge temperature gradient as the heat flux is increased. The H–mode power threshold is found explicitly in terms of the parameters in the thermal conductivity expression. The scaling of the H–mode power threshold with the plasma parameters is studied.

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MHD computation of feedback stabilization of helical modes*

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There remain open questions concerning the role of a conducting wall on laboratory plasmas. How do MHD mode evolution, plasma parameters, and dynamo phenomena depend on RFP boundary conditions? Related questions in tokamaks include the role of conducting plate stabilization of external kinks in the second stability regime.

A 3D, resistive, nonlinear MHD code has been modified to include perfectly conducting feedback windings, targeting any number of MHD modes in an RFP. This model can isolate effects of individual modes and groups of modes on plasma evolution. In particular, the code can predict the simplest effective configuration of feedback windings for RFP sustainment in the absence of a conducting wall.

Passive feedback stabilization of a small, select number of dynamo modes transfers energy to their neighbors, which become dominant to sustain reversal. There is a small range of candidate dynamo modes; when these are simultaneously stabilized, growth of all modes drops. Nearly optimum RFP plasma performance is restored, without the severe operational constraints imposed by a conducting wall.

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Global, 1-D, Kinetic Stability for FRC Equilibria*

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The kinetic linear stability of an FRC is complicated by the fact that the local approximation is not valid in 2 regions: near the field-null, where ion orbits may be large and near the separtrix, where gradients may be very large. A global theory developed by Lewis and Schwarzmeier has been implemented in a computer code to analyze FRC stability. The code seeks a solution to the linearized Maxwell-Vlasov equations in the form of eigenvalues to a dispersion matrix. The dispersion matrix contains all the information pertaining to the stability of the plasma. In this poster the dispersion matrix for both a uniform and reversed field plasma will be compared.

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1C33

The Ambipolar Structure of the Reversed Field Pinch *

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A multi-energy-group trial model† is used to investigate the ambipolar structure of the Reversed Field Pinch. A resistive low-temperature plasma is assumed to drift radially inwards from the wall, and hot electrons and ions are assumed to leave the pinch along stochastic magnetic field lines. The Rechester-Rosenbluth diffusivity and an associated mobility are used to compute the radial fluxes of hot electrons and ions in the ambipolar radial electric field. By applying quasi-neutrality, particle balance and power balance to the outer portion of the plasma volume (wherein cold plasma has not yet been heated), the following features are uncovered.

1. The radial electric field has a global structure with a characteristic profile.
2. The potential difference between the core and the edge is on the order of the hot electron energy.
3. There is a characteristic radial drift velocity of incoming plasma, which is always smaller than the (E_z/B_θ) drift velocity.
4. There are characteristic density profiles of incoming and outgoing plasmas.
5. There is a characteristic temperature ratio of the heated plasma to the incoming plasma.

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† Suggested by R. W. Moses, Jr.

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A Parallel 2D Electrostatic PIC Code for the Mark III Hypercube *

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We have implemented a 2D electrostatic plasma particle in cell (PIC) simulation code on the Caltech/JPL Mark IIIfp Hypercube. The code simulates plasma effects by evolving in time the trajectories of thousands to millions of charged particles subject to their self-consistent fields. Each particle's position and velocity is advanced in time using a leap frog method for integrating Newton's equations of motion in electric and magnetic fields. The electric field due to these moving charged particles is calculated on a spatial grid at each time step by solving Poisson's equation in Fourier space. These two tasks represent the largest part of the computation. To obtain efficient operation on a distributed memory parallel computer, we have used the General Concurrent PIC (GCPIC) algorithm [1] previously developed for a 1D parallel PIC code.

The advance in time of the particle velocities and positions (the "push") represents the largest fraction of the total computation. To obtain efficiency on the hypercube, particles are partitioned evenly among processors. If each processor keeps a copy of the entire field grid, the simulation will remain load balanced for the duration of the computation. This static decomposition has the drawback of requiring redundant memory usage for all field related quantities, and limits the size of the simulation which can be done. Redundant computation related to field quantities also limits the efficiency.

The field solver is the next largest fraction of computation to be done. We solve Poisson's equation in Fourier space by using a 2D parallel FFT algorithm. The rectangular field grid is first divided among the processors by rows so that 1D FFTs along each row can be done in parallel without communication. The grid is then redistributed by columns so that the FFTs for the second dimension can also be done in parallel. Poisson's equation is then solved in parallel by columns. The inverse 2D FFT returns the grid to its original partitioning.

A more efficient use of processor memory can be obtained by partitioning both the field and the particles among the processors. As particles evolve in time, they may traverse the entire spatial grid, so in this decomposition it is necessary to pass particles from one processor to another as they move through the problem space. Non-uniformities can also develop during the course of a simulation which will degrade the load balance and reduce efficiency. However, since one of the spatial dimensions of the simulation is periodic, large scale non-uniformity is not expected in this coordinate. By partitioning the field grid along this direction, load imbalance is not expected to be a problem since on average, the number of particles entering a processor will equal the number of particles leaving a processor.

We will present an overview of the parallel algorithm and the techniques used to parallelize the code. Results related to the efficiency of the code on the Mark IIIfp Hypercube Concurrent Computer will be discussed.

*Work supported by the Applied & Computational Mathematics Program, DARPA

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Anomalous Transport in the Hot Ion H–Mode

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Recent experiments on DIII–D [1] have obtained H–modes with ion temperatures much larger than electron temperatures in the bulk of the plasma by operating with low density. It is also found that the ion thermal conductivity is substantially smaller than the electron thermal conductivity ($\chi_e \gg \chi_i \simeq 2$ to $3\,\chi_{neo}$). These observations are not obviously consistent with the standard anomalous transport model in which the η_i mode plays a dominant role, even for losses in the electron channel. In the present case, the η_i mode is expected to be weak. Further, the usual dissipative trapped electron mode vanishes in the flat density limit found in the H–mode. Hence, the mechanisms that comprise the usual drift wave transport model are small effects for the hot ion H–mode, and additional physics is required. Here, we point out how the hot ion H–mode could fit into the drift wave transport model. It is first noted how the familiar η_i mode is strongly stabilized in the regime $T_i \gg T_e$. It is then shown that the source of fluctuations responsible for the observed $\chi_e \gg \chi_i$ could be an unstable trapped ion mode. The distinguishing feature of this mode is the ion response is nearly adiabatic. Quasilinear estimates of the particle and energy fluxes show that this model is consistent with the observation $\chi_e > \chi_i$.

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Onset of the H - Mode and Resistive MHD Stability*

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The L to H mode transition in tokamaks is observed to be accompanied by a drop in the low m magnetic signal. This is consistent with stabilization of collisional drift tearing modes and resistive ballooning modes in the edge layer. Both kinds of mode are stabilized when a critical edge temperature is reached. The value of ν_* required for stabilization is ≈ 10, as in experiments. The critical temperature is roughly linear in magnetic field strength for tearing modes, and is independent of the magnetic field strength for resistive ballooning modes.

Tearing modes could be destabilized by a large edge current gradient. The resistive layer width for collisional drift tearing modes is large, $\approx$ 1cm in the edge region, and modes can saturate quasilinearly at large amplitude by local flattening of the temperature profile. The saturation amplitude depends on the linear growth rate; modes will disappear when they are linearly stable. Sheared rotation can be stabilizing, independent of sign, and lower the critical temperature for linear stability.

The spectrum of electrostatic resistive ballooning modes shrinks to a single mode with $m \approx 10$ as its critical temperature is approached. In this case too, rotation lowers the critical temperature, independent of sign. This is consistent with the CCC experiment, in which rotation produced an L - H transition. Viscosity restricts these modes to the edge layer and eliminates the drift regime of this mode.

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COLLISIONNAL TRANSPORT IN BRAIDED MAGNETIC FIELDS

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Particle diffusion is studied in a case where magnetic surfaces are destroyed and where collisionnal effects cannot be entirely neglected.

It is shown that, for rather general collisionnal operators and in the absence of radial electric field, a variational principle may be used to obtain the diffusion coefficient. The method is applied to a simple model of magnetic perturbation for which the diffusion coefficient can be computed analytically in asymptotic limits. The results will be compared with the existing formulas.

For this simple magnetic perturbation it will be shown than it is also possible to evaluate the effects of a radial electric field and of a time dependant magnetic perturbation.

SHERWOOD THEORY MEETING 1990

Analytical Stability Boundary for Δ'-Type Resistive Ballooning Modes at High Beta*

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Analytical expressions for the marginal stability boundary for Δ'-type incompressible resistive ballooning modes at high beta are obtained in the limits of both large and small global shear. In the large shear limit, the ballooning mode equation in canonical form can be solved by means of a point interaction approximation,[1] with the solution iterated as in Born scattering theory. In this limit the behavior of the solution at the nearest point of zero local shear controls the determination of marginal stability, here assumed to be given by the condition $\Delta' = 0$. In the limit of small global shear, the averaged ballooning mode equation is shown to reduce to the Mathieu equation, which can then be solved exactly for the quantity $\Delta'(\alpha, S)$, where $\alpha = -(2Rq^2/B^2)(dp/dr)$ is the normalized pressure gradient and $S = (r/q)(dq/dr)$ is the global shear. Finally, we numerically solve the ballooning mode equation for arbitrary shear to obtain the quantity Δ', maximized with respect to the radial wavenumber θ_0 of the ballooning mode representation. The analytical results are found to agree very well with the numerical solution. These results show that the Δ'-type resistive ballooning modes are stable throughout most of the regime corresponding to ideal ballooning "second stability" in high-beta tokamaks.[2] Since resistive ballooning modes may be a candidate for interpreting some aspects of confinement degradation with auxiliary power in the first regime of stability (where they are largely unstable), this result suggests that confinement in the second stability regime could be favorable for tokamak profiles that can access it.

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Turbulent MHD Relaxation With Cross Helicity*

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The selective decay and dynamic alignment processes drive a decaying magnetofluid to states which minimize the energy integral under the constraints of constant cross and magnetic helicity.[1] Montgomery, Turner and Vahala[2] conjectured that back transfer of magnetic helicity by nonlinear couplings[3] in the dynamical equations was the mechanism that lead to selective decay. This was deduced after it was shown that in ideal (nondissipative) MHD the magnetic helicity spectrum underwent a *bose like* condensation into the the the longest wavelength of the system in the limit where the number of degrees of freedom of the system was taken to infinity. We extend this work by including cross helicity in the ideal MHD calculations and find that the cross helicity spectrum experiences a "partial" condensation into the longest wavelength in the infinite system limit when magnetic helicity is present. The cross helicity partial condensation is differs from the magnetic helicity condensation in that some cross helicity remains in the short wavelength portion of the spectrum. This suggests the possibility that cross helicity is back transfered when magnetic helicity is back transfered, and that cross helicity back transfer could lead to growth of the normalized velocity magnetic field correlation (i.e. dynamic alignment).

A simple model of 3D MHD decay is developed from the ideal MHD spectra. With the model a function is derived that maps initial states onto the time asymtotic states produced by the selective decay and dynamic alignment processes. The predictions of the decay model are shown to agree well with simulations of a Galerkin model of 3D MHD decay.

*Work supported in part by NSF grant ATM-8913672 and the NSA Space Theory Program. TS is supported by the NASA Graduate Student Researchers Program.

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Full-Wave and Ray Tracing Studies of Ion Cyclotron Heating and Current Drive in Tokamaks*

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A three-dimensional, full-wave ion cyclotron RF (ICRF) code [1] has been implemented at MIT. This code employs a semi-spectral approach to solve the ICRF wave propagation and absorption problem in toroidal geometry. Ion Bernstein wave fields are solved for directly. This code has been used to study different antenna configurations (monopole and dipole) for the proposed Alcator C-MOD ICRF experiment. Hydrogen minority heating in a deuterium majority plasma was studied in the range of parameters $f_o = (80 - 120)$ MHz, $B_\phi = (5.3\text{-}8.0)$T, $n_e(0) = (3 - 10) \times 10^{20}\mathrm{m}^{-3}$, $n_H/n_e \leq 0.04$, $a = 0.21$m, $R_o = 0.665$m, $\kappa=1.8$, $\delta=0.3$, and $I_p = (1-3)$MA. Monopole and dipole antenna configurations were found to give similar power deposition profiles with the monopole loading resistance ($R_L \simeq 10-12\Omega$) about a factor of two higher than the dipole loading ($R_L = 4-6\Omega$), (either in phase or out of phase). Results will be presented for antenna loading as a function of the properties of the plasma scrape-off-layer (SOL) and for minority absorption at different toroidal fields and frequencies.

In addition to full-wave studies of ICRH, we have started to apply the full-wave code [1] and the ACCOME/LHRF package [2] to fast wave current drive scenarios (at $\omega/\omega_{CD} \gtrsim 10$) in JFT-2M [3] and the proposed DIII-D experiments. [4] The parameters for these experiments are typically $B_\phi = (1 - 2)$T, f_o=(60-200) MHz, $n_e(0) > 1 \times 10^{19}\mathrm{m}^{-3}$, and a deuterium plasma. Comparisons of wave propagation and absorption will be made based on the behavior of individual ray trajectories and the predictions of the full-wave ICRF model. In particular, attention will be focused on the $n_{||}$ behavior of individual rays which may decrease significantly due to toroidal effects, resulting in a drastic reduction in the single pass absorption of the waves. (Here, $n_{||} = k_{||}c/\omega$ is the parallel refractive index.)

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Particle Simulations Of Transport In A Diverted Tokamak Scrape-Off Layer: The High-Recycling Regime*

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The transport of particles and energy through a tokamak scrape-off layer (SOL) is studied via the particle simulaton code **DIPSI** (Direct Implicit Plasma Surface Interactions). This code combines direct-implicit particle-in-cell (PIC) techniques with Monte Carlo models for Coulomb collisions, and charged/neutral atomic physics interactions. The fully-kinetic guiding-center PIC code provides a self-consistent solution of the electrostatic potential profile in one spatial dimension (along the open field lines in the SOL) and two velocity components $(v_\parallel, v_\perp)$.

The Monte Carlo, binary-particle Coulomb collision model conserves both the momentum and kinetic energy of the interacting particles. The full range of Coulomb collisional processes (e-e, e-i and i-i) are included. Recycled neutral particles are treated in an *ad hoc* manner: the density is assumed to decay exponentially with increasing distance from the divertor plate (the e-folding length is taken to be the average mean-free path to ionization) and the temperature of the neutrals is prescribed by the user. The neutral particles interact with the background plasma via charge-exchange events with ions and impact ionization events arising from electron/neutral collisions.

This model is used to determine the effect of charged/neutral interactions on the transport properties of a tokamak SOL plasma. The prescribed neutral particle density will span a wide range of recycling fractions. Values of the presheath and collector sheath potential drops, plasma temperature, flow velocity and parallel heat fluxes as a function of charged/neutral collisionality will be presented.

We will also discuss the possibility of extending this model to include the effects of sputtered impurity particles, which could be evolved as a second ionic species. This would allow one to determine the effect of sputtered impurities on the potential profile (and ultimately, the transport of particles and energy) in the plasma-sheath region.

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DISSIPATION RANGE SPECTRA IN SPACE AND LABORATORY PLASMAS WITH IMPLICATIONS FOR CHARGED PARTICLE DIFFUSION AND TRANSPORT

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Quasilinear theory expressions for the Fokker-Planck coefficient for pitch-angle scattering of energetic charged particles by turbulent magnetic fields provide a basis for discussions of many basic plasma physics processes including the problem of spatial diffusion of energetic charged particles. These expressions employ the magnetic field power spectrum, or equivalently, the correlation function of the turbulence. Changes in the power spectrum, even if they occur at the smallest length scales represented by the spectrum, can have profound effects on particle diffusion rates as derived from quasilinear theory. In order to examine the relationship between magnetic power spectra and quasilinear theory implications for energetic particle diffusion, we turn to interplanetary data sets where in-situ measurements are readily available.

A technique has been developed for the analysis of magnetic field spectra that is based upon the structure function of the turbulence. This technique demonstrates a greater degree of accuracy when dealing with rapidly changing spectral slopes than does the standard Blackman-Tukey or FFT analyses. We have used this technique to look at high resolution data from the Voyager 1 and 2 and Mariner 10 spacecraft. We report evidence of resonant dissipation with the ambient proton population leading to a steepened spectral form. The onset of a dissipation dominated spectrum marks the end of the inertial subrange and represents the ultimate fate of the energy contained there.

The standard expressions for the magnetostatic limit of the linear resonant quasilinear theory of pitch-angle scattering of charged particles are reexamined in light of these observations. We find that particle diffusion is not supported by these expressions, thereby demonstrating the basic flaw in the magnetostatic linear resonant theory.

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MULTIPLE MODE CONVERSION*

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The Friedland Reduction Algorithm [1], applied to the generalized local dispersion tensor $\mathbf{D}(\mathbf{k},\omega;\mathbf{x},t)$ for linear waves in a multi-dimensional nonuniform medium, converts the problem to a succession of pair-wise mode conversions. Each conversion occurs at the intersection of a ray of one mode (say, a) with the dispersion surface $D_b(k,x) = 0$ of another mode (b). Although a *single* conversion can be exactly solved [2] to obtain a coordinate-independent result, for *multiple* conversions heuristic methods have been used to obtain analytic results [3-8]. In the present work, we investigate the validity of such heuristic approaches, by studying a model problem numerically. Our aim is to find a simple validity criterion for expressing the multiple-mode S-matrix in terms of the individual S-matrices of the pair-wise conversions. Our chief motivation is to validate our model of ion-gyroresonance heating in terms of successive conversions among collective and ballistic modes.

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Equilibrium Studies using a Two-Fluid Drift Wave Turbulence Model*

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We present a theoretical and numerical investigation into the equilibrium solutions of the non-dissipative homogeneous Hasegawa-Wakatani equations.[1,2] These solutions are of interest for several reasons: First of all they allow us to check that the simulation code conserves the 4 invariants which the system possesses: the kinetic energy, the enstrophy, the density variance, and the cross-correlation of the density with the vorticity. Furthermore, the k-spectra of the equilibrium potential and density fluctuations give us an indication of the direction towards which the nonlinearity tends to drive the system. Finally, one of our ultimate goals is to gain some insight into the effect of the finite cross-correlation. In the equilibrium runs we can manipulate the cross-correlation directly and observe how it changes the evolution of the system.

When the dissipationless, homogeneous system is in equilibrium, methods of equilibrium statistical mechanics (ESM) may be used to predict the equilibrium spectra.[3] We have found that one must exercise caution in interpreting the results of certain standard ESM methods. We elucidate what precautions must be taken in applying the theory, and give predictions for the spectra. These results are verified numerically. There are implications to the disequilibrium problem as well, which we discuss.

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TRANSPORT OF ELECTRONS IN BIFURCATED TOKAMAK EQUILIBRIA

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Monte Carlo calculations of transport have been performed in bifurcated tokamak equilibria computed using a stellarator code. Time-averaged equations of electrostatics and magnetostatics serve to model turbulence. The electric field is determined from the requirement of quasineutrality rather than Ohm's law. Terms in the electric potential amounting to less than one percent of the temperature can reduce the confinement time by several orders of magnitude in axially symmetric equilibria. Small three-dimensional asymmetries in the magnetic field similarly bring theoretical predictions of transport into a more realistic range. Comparisons have been made with measurements in the PLT and TFTR experiments. In both the calculations and the measurements anomalies spread the data out by a factor of two or three. However, the most pessimistic theoretical values of the energy confinement time agree with the most optimistic experimental values.

Neoclassical Resistive MHD Equations in General Toroidal Geometry

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The linearized neoclassical resistive MHD boundary layer equations are derived using the ballooning mode representation and flux-surface averaging in general toroidal geometry. Our equations include the effects of the compression, diamagnetic drift as well as the neoclassical viscosity and are fully electromagnetic. In these aspects, the set of the equations is a highly advanced model of the resistive layer dynamics, and can be used for the study of problems such as the compressiblity effect of the neoclassical resistive mode found by Callen *et al*[1], and the neoclassical viscosity effect on the conventional resistive interchange, ballooning and tearing modes. For such problems a numerical work is in progress, and the results will be given in future.

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Amplification of Resonant Perturbations in Tokamaks*

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Recent experimental results[1] indicate that tokamak error fields can have a strong effect on locked mode thresholds, and may also have a significant effect on tokamak confinement even in the absence of locked modes. We are studying the effects of external perturbations on tokamak islands with the three-dimensional PIES code. Plasma currents adjust self-consistently in the presence of external perturbations and islands. The boundary conditions are calculated from deformed external circular coils, modeling installation errors in tokamak PF coils. We find that the plasma generally amplifies the perturbation, even in the absence of tearing modes. An analytical model is used to understand this effect. We discuss the effects of current profile, cross-section shape, and pressure on the island widths.

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A Model of Sheath-Driven Impurity Production by ICRF Antennas*

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The release of impurities during ICRF heating can be attributed to two kinds of mechanisms: *global* production caused by additional power flow in the scrape-off layer (SOL) and *local* release from the vicinity of the antenna. The latter process is particularly important in understanding the origin of metal impurities in ICRF experiments. Recent theoretical work has suggested that the primary local mechanism for impurity generation is physical sputtering of the Faraday screens (FS) of the powered antennas by ions accelerated in rf sheaths.[1] Here, we describe an impurity production model which allows quantitative comparison with experiment and show that the model gives good agreement with JET data on the local metal impurity influx for a wide variety of operating conditions. Comparison with the experimental dependence on phasing, magnetic field angle, density and voltage is given for different FS geometries (flat or V-shaped) and FS coatings (Cr/Ni or Be).

The model includes the physics of ion acceleration in rf sheaths, physical sputtering (and self-sputtering) of the material surfaces on which sheaths form, and the relevant SOL physics (neutral flow, ionization, ion radial transport and ion acoustic flow along field lines). The metal impurity influx is found to depend sensitively on the antenna voltage and phasing, the local density at the screen, and the self-sputtering coefficient of the Faraday screen coating. For materials with high atomic mass (e.g. Cr, Ni, Mo), the model predicts a large increase of the metal influx at high density and antenna voltage due to self-sputtering. When the self-sputtering yield exceeds a threshhold of order unity, the number of sputtered neutrals increases without bound ("avalanche") in a constant T_e model. Electron energy balance in the SOL provides a saturation mechanism for the influx. The implications for high-density ICRF operation (C-MOD or CIT) will be discussed, and the effectiveness of low mass FS materials (Be or C) and dipole antenna phasing in eliminating the metal influx problem will be illustrated.

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SHERWOOD THEORY MEETING 1990

3-D Simulation of η_i Modes in a Sheared Magnetic Field (Slab Geometry)*

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A numerical spectral code based on the gyrokinetic equations has been written to simulate the nonlinear evolution of η_i modes. The parameter regime of interest is that near marginal stability where low noise levels are essential and kinetic effects must be included. Spectral methods are useful when only a finite number of modes dominate the dynamics. The nonlinearities can be isolated and studied individually in order to assess their relative importance in saturating linear instabilities and in energy transfer among the modes. Thus, this code could serve as a diagnostic complement to particle codes in helping to elucidate the underlying nonlinear processes, and if convergence tests and comparison with particle codes provide evidence that η_i turbulence can be modelled with a modest number of modes, it could also be used for investigating the scaling of energy transport with plasma parameters. A compromise has to be made between the number of modes and the need to complete a run in a reasonable time. In this code, the localized fields of the unstable η_i modes are represented in terms of Hermite functions (which are close to being linear eigenmodes). The most unstable η_i modes are positioned at mode rational surfaces, separated one larmor radius apart. Neighboring modes overlap and are allowed to interact with each other through coupling to damped ion acoustic modes. The effect of this nonlinearity in saturating the linear instabilities is being explored, and the energy transport at saturation observed. Preliminary results for "realistic" parameters ($\eta_i = 2$, $L_n/L_s = .05$, $\rho/L_n = .01$, $T_i/T_e = 1$, $T_i = 1\,\text{kev}$), with unstable modes at seven mode rational surfaces, suggest that thermal diffusivities are of the order of $(\text{meter})^2/\text{sec}$.

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

Selective Decay and Isolated Coherent Structures. WILLIAM H. MATTHAEUS, W. TROY STRIBLING, DANIEL MARTINEZ, SEAN OUGHTON, *Bartol Research Institute, Univ. of Del.* and DAVID C. MONTGOMERY *Dept. of Physics and Astronomy, Dartmouth College.** Turbulent relaxation mechanisms known as selective decay processes[1,2,3] have been proposed as a dynamical explanation for relaxation in toroidal discharges and a basic charateristic of turbulence in both two and three dimensional MHD and in two dimensional (2D) hydrodynamics. A common feature of these conjectures is a prediction that the flows evolve towards a state in which ratios of certain ideal quadratic global invariants attain extremal values. In the simplest case of 2D hydrodynamics, selective decay implies minimal Ω/E (enstrophy/energy) and the theory is closely related to dynamical evolution suggested by Batchelor[4]. Recently, the suggestion has been made[5] that at high Reynolds number (R) the emergence of isolated coherent structures, i.e., isolated vortices, thwarts this process by prematurely and permanently eliminating the nonlinear couplings that give rise to turbulence. We have numerically investigated the nature of this relationship between coherent structures and turbulence by computing solutions of the 2D incompressible Navier Stokes equations at high $R \approx 14000$ (based on a box dimension) and for long times (> 200 initial eddy turnover times) using a 512^2 spectral method code. We find that the selective decay process, characterized by merger of like signed vortices, production of larger streamline patterns and monotonic descrease of Ω/E continues throughout the simulation. Isolated vortices appear and cause turbulence to become spatially and temporally intermittent after about $t = 30$. However, by $t = 210$ the final vortex merger has been accomplished, leaving just two opposite signed large scale flow structures. An interesting and not entirely expected feature of the computation is the persistence of a particle-like character of the vorticity distribution at long times. The arrangement of the vortices somewhat suggests an Ewald lattice[6,7]. The system is asymptotically approaching the configuration predicted by selective decay. This gives evidence that coherent structures do not halt turbulent relaxation, but rather are an essential part of the bidirectional wavenumber transfer that is characteristic of selective decay. This interpretation may also have important implications for MHD systems and others to which selective decay conjectures have been applied.

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Independent Determination of β_p and l_i for Nearly Circular Tokamaks and RFP's

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We have recently shown how the elongation and triangularity of tokamak equilibria may be related to plasma pressure and current profiles[1]. This formulation shows that the elongation scales as ϵ^2 and the triangularity as ϵ^3, where ϵ is the inverse aspect ratio. The same formulation can be used in order to express the radial and poloidal magnetic fields on the plasma surface in terms of plasma profile parameters and the geometrical parameters.

When expanded on the plasma surface to second order in ϵ, we show that the radial and poloidal fields can be written, respectively, as:

$$B_r = B_{r1}\sin\theta + B_{r22}\sin 2\theta,$$
$$B_\theta = B(a) + B_{\theta 1}\cos\theta + B_{\theta 20} + B_{\theta 22}\cos 2\theta,$$

where θ is the poloidal angle coordinate. In the above,

$$B_{\theta 1} = \epsilon B(a)(\beta_p + \frac{l_i}{2} - 1) \tag{1}$$

and B_{r22} and $B_{\theta 22}$ are functions of β_p, l_i and κ, the elongation of the plasma surface. The latter can be eliminated analytically to give the following equality:

$$c_1 B_{r22} + c_2(l_i)B_{\theta 22} = Q_0(l_i) + Q_1(l_i)\beta_p + Q_2(l_i)\beta_p^2, \tag{2}$$

where c_1 is a known constant while c_2 and the Q_i are known functions of l_i. We then use Eq. (1) to eliminate β_p in Eq. (2), and obtain a (non-linear) equation for l_i. This can be solved whenever the radial and poloidal magnetic fields are measured in a sufficient number of locations so that their second fourier harmonics are available. It should also be noted, that if a diamagnetic measurement is available in addition to the above, the width of the pressure profile can also be determined.

Examples will be given.

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Vertical Stability Analysis of Highly Elongated DIII–D Discharges

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DIII–D has recently been operated with a discharge reaching an elongation of $\kappa \sim 2.5$ before disrupting via an axisymmetric instability. Single and multifilament stability analyses indicate that the discharge was well within the ideal stability limit and should have been easily maintained by the control system. On the other hand, the full ideal MHD stability code GATO predicts that, just prior to the disruption, the equilibrium was extremely close to the ideal limit. The mode structure computed by GATO is in good agreement with data from the disruption and shows considerable deviation from a rigid shift; the unstable displacement has large $m \neq 1$ poloidal components, especially $m = 3$, as well as a finite variation across the discharge. The results are in contrast to those obtained for slightly less elongated, but much less triangulated, equilibria which are predicted to be close to the ideal limit by both the rigid shift models and GATO.

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Alfvén Gap Mode Model

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For an ignited plasma the presence of α particles can affect the stability properties of the equilibrium configuration. In particular, toroidicity induced shear Alfvén waves can resonantly interact with circulating alphas and be destabilized. A new formulation of the energy principle has been derived by assuming fluid bulk plasma and fully kinetic α particles. This model can be viewed as an extension of the Vlasov fluid model [1]. We consider systems in which the alphas are essentially collision free on the shear Alfvén time scale and therefore are treated by the Vlasov equation. Furthermore, we assume there are sufficient collisions on the MHD time scale so that electrons cannot stay resonant with any low frequency waves. The α particles enter the momentum equation for the bulk plasma in the expression of the electromagnetic force: $(\mathbf{J}_e + \mathbf{J}_i) \times \mathbf{B} = (\nabla \times \mathbf{B}) - \mathbf{J}_\alpha \times \mathbf{B}$ where $\mathbf{J}_\alpha$ is defined as $\mathbf{J}_\alpha = \int q_\alpha \mathbf{v} f_\alpha d\mathbf{v}$. The equilibrium distribution function for the alphas is assumed to depend on the total energy of the particle ϵ and its toroidal canonical angular momentum P_ϕ, through the following combination $f(\epsilon + \Omega p_\phi)$, where Ω is a rigid angular velocity for the circulating alphas. We found that the alphas affect the MHD equilibrium through the pressure and a centrifugal force term. We investigated linear stability and we derived a combination of definite positive terms, representing the MHD δW and the α contribution. This provides a very powerful mean to test linear stability. In particular, a necessary and sufficient condition for stability, in the context of this model, is given by $\delta W_{MHD} \geq n^2 \Omega^2 K_{MHD}$. Since Ω is directly related to $\omega_{*\alpha}$, this stability criterion exactly reproduces that found by Fu and Van Dam [2].

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Statistical Mechanics of Coulomb Systems in Finite Space*

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The canonical equilibrium measure of classical two-component Coulomb matter with regularized interactions is rigorously analyzed in a finite volume. The parameters of the regularization like depth of the two particle potential V and smoothing length are chosen such as to mimic stabilizing quantum effects. The physical motivation for this investigation is the following: because of the long-range character of the Coulomb force it can be estimated that the thermodynamic behavior in a finite volume should in some (not all) respects differ qualitatively from that predicted by the standard thermodynamic limit. First the mean-field approximation is discussed, and it is shown that in the corresponding mean-field regime the one-particle density is inhomogeneous on a new characteristic length scale, λ_{inh}. For a system of N positive and N negative particles, λ_{inh} and the characteristic length scale of correlations, λ_{corr} (= Debye screening length), are related via $\lambda_{inh} = (2N)^{1/2}\lambda_{corr}$. The major conceptual conclusion that is drawn from this is that one needs at least two nontrivial complementary thermodynamic limits to define the equilibrium thermodynamics of two-component Coulomb systems. One of them is the standard thermodynamic limit (infinite volume), which can be characterized by the shorthand formula: $N \to \infty$, λ_{corr} fixed. Its complementary limit is characterized by $N \to \infty$, λ_{inh} fixed. This limit is conveniently performed in a finite volume, and turns out to be an inhomogeneous mean-field limit. The proof of that limit is outlined and its governing equations are discussed.

The most prominent new feature in the mean-field thermodynamic limit, which is absent in the standard thermodynamic limit, is an anomalous first-order phase transition where the Coulomb system explodes or implodes, respectively. For the transition temperature $T_{\updownarrow}$ one finds the estimate

$$k_B T^* > k_B T_{\updownarrow} > V(2a_0)/6\ln(R/a_0)$$

for a_0/R small enough. Here $T^* \sim a_0^{-1}$ stands for the ionization temperature, a_0 for the size of a particle, and R for a typical radius of the system. The phase transition is associated with the existence of a strongly inhomogeneous metastable plasma phase far below the ionization temperature. Some analogy arguments reveal that the phenomena should be present in a quantum mechanical treatment of the problem as well. Possible applications to realistic systems will be pointed out.

Ref.: *A Complementary Thermodynamic Limit for Classical Coulomb Matter*, scheduled to appear in *J. Stat. Phys.* **59**: Issue 5/6 (1990).

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FOKKER-PLANCK MODELLING OF THE LOWER-HYBRID CURRENT DRIVE AND ITS INVESTIGATION USING CYCLOTRON RADIATION

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Abstract

The solution of the Fokker-Planck quasilinear equation describing lower-hybrid current drive is obtained numerically using a 2-D code. It is shown that the current carrying superthermal tail has in general a counter-current component resulting from pitch-angle scattering and imperfect one-directional wave launching. This new feature of the fast tail makes emission and transmission of cyclotron radiation normal to the magnetic field unsuitable for diagnosing the energetic electron population. The appropriate diagnostics must rely on emission and/or transmission of electron- cyclotron wave away from normal.

Discussion of Kink-Tearing Mode Relation*

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An elegant asymptotic solution exists in the literature[1] of the kink-tearing mode equations which leads to an analytic dispersion relation[1] when the layer width for electron conductivity is less than the width of the perturbed inertia layer, x_A. The physics of these equations also include finite Larmor radius effects using the Padé approximation which is important if x_A becomes comparable to the ion Larmor radius. These equations have been frequently used to describe the effects of hot particles on the MHD stability of the $m = 1$ kink mode. In this work we discuss the accuracy of the asymptotic dispersion relation. We show that when x_e/x_A is of modest size, $\lesssim 0.2$, the asymptotic solution can have serious accuracy problems, and cause mode structure and stability conditions to differ considerably from that obtained from precise numerical studies. We have also "empirically" altered the form of the analytic dispersion relation and find we can obtain a considerably more accurate analytic solution than the rigorous asymptotic expression. The empirical dispersion relation allows a more rapid scan of stability boundaries than would be possible with a shooting code.

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ION-TEMPERATURE-GRADIENT MODES IN THE LONG WAVELENGTH LIMIT

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Several experimental observations suggest that the ion temperature gradient driven mode, the so-called ∇T_i-mode is a possible candidate for the explanation of anomalous ion energy transport in tokamaks. Most of the analyses of this instability have considered the short-wavelength limit $(k_\theta \rho_i)^2 \sim \varepsilon_{Ti}^{1/2}$, with $\varepsilon_{Ti} = L_{Ti}/R$. The long-wavelength limit has received less interest. Nevertheless, such limit is relevant for transport studies because modes at longer wavelengths are expected to produce larger transport. In addition, long wavelength coherent structures have been observed in ∇T_i-mode simulations. Such structures can be analyzed only by using a proper modelling of the ∇T_i-mode dynamics at low values of the perpendicular wavenumber.

In the present paper we investigate this limit for flat density profiles and demonstrate, in the fluid-ion approximation, the existence of two types of eigenmode structure; one is toroidicity-induced and another is slab-like. The slab-like ∇T_i eigenmode is reactively unstable and becomes stable for $k_\theta \rho_i \gtrsim 10^{-1} \varepsilon_{Ti}^{1/4}$. The toroidicity-induced ∇T_i eigenmode, meanwhile, contains two unstable branches. One is the negative-frequency branch, which propagates in the ion diamagnetic-drift direction and is reactively unstable. Another is the positive-frequency branch, which propagates in the electron diamagnetic-drift direction and is destabilized via electron nonadiabatic dynamics. Both branches tend to be stabilized in the very long wavelength limit, $k_\theta \rho_i \lesssim \varepsilon_{Ti}^{3/4} \tau/\sqrt{3}q)$, q being the safety factor and τ the ratio between electron and ion temperature. In this extreme limit, however, the parallel incompressibility assumption, $|\omega| > |\omega_{ti} = v_{Ti}/qR|$, becomes violated, and the fluid-ion approximation is no longer valid: the ion kinetic effects could play an important role. For shorter wavelengths, $k_\theta \rho_i \gtrsim \varepsilon_{Ti}^{1/4}$, while the negative-frequency unstable branch persists, the positive-frequency branch becomes stabilized.

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Analytic Solutions of Fringing Fields for an Ion-Bernstein Wave Antenna with Faraday Screen

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The function of a Faraday screen for an ion-Bernstein wave antenna is to shield out the poloidal electric field component allowing only the parallel electric field to penetrate and couple to the ion-Bernstein wave inside the plasma. Realistic geometry of a screen consists of conducting strips oriented in the poloidal direction and separated by free space. Such arrangement can generate spiky fringing fields which can couple to short wavelength electrostatic modes. These modes can be damped in front of the antenna or propagate to undesirable locations thus channeling rf power away from the interior of the plasma. For this study, the fringing fields are analytically calculated (a) for $(k_{\parallel}\lambda_{De})^{-1} \ll 1$ or $(k_{\parallel}\lambda_{De})^{-1} \gg 1$ when the wave equation is describable by Laplace's equation, and (b) for $(k_{\parallel}\lambda_{De})^{-1} \sim 1$ when it becomes the Klein-Gordon equation. These equations are solved using Green's function methods and analytic solutions of the fringing fields are obtained. Variation of the fringing fields with screen parameters as well as the characteristics of the Fourier spectrum will be discussed.

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Entropy Production and Variational Bounds on Fluctuations

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The relaxation of a plasma in a reversed–field–pinch in the presence of a turbulent e.m.f. is an example of relaxation phenomena in nonlinear diffusive systems. Recently, we have obtained, from first principles, an "entropy production" functional which can provide a basis for the calculation of relaxed states.[1] We show, in this paper, that the entropy principle can be used to obtain variational bounds on fluctuations. The procedure has mathematical similarities with "optimum" theories of bounds,[2,3] but is more physical. We illustrate the use of the method for two problems — heat transport by turbulent convection and relaxation of a reversed–field–pinch.

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Variational Principle for Vlasov Equation on a Symplectic Leaf *

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Vlasov equation is a Hamiltonian system with Lie-Poisson structure.[1] The Lie-Poisson bracket is degenerate and admits an infinite number of invariants, called Casimirs, which foliate the space of the distribution functions into invariant subspaces called symplectic leaves. The actual dynamics is thus constrained to a single leaf. It is desirable to project out the Casimir invariants and express the Vlasov equation in terms of the coordinates on such a leaf. Recently Crawford and Hislop[2] worked out a perturbative scheme for the Vlasov-Poisson equation near an appropriate equilibrium. We apply the Hamilton-Jacobi formalism developed by Pfirsch and Morrison[3] to this problem, and derive a (fully nonlinear) variational principle in terms of the leaf coordinates. Our approach is more general than that taken by Crawford and Hislop, and we will make connections with their result. This variational principle has proven to be a useful tool in studying the stability problems of Vlasov-Maxwell system;[4] it is also useful for deriving gyroresonance[5] and quasilinear equations.

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Interaction Mechanisms in Drift Wave Turbulence

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The traditional conceptual paradigm of drift wave turbulence is that of 2D fluid turbulence, in which the simultaneous conservation of enstrophy and energy forces a dual cascade of the former to small scales and the latter to large scales. However, since drift waves are dispersive (strongly so at $k_\perp \rho \sim 1$), non-local (in $\underline{k}$, ω) wave-wave interaction processes, which need not result in self-similar transfer, are potentially important as well. Moreover, the fact that most measured spectra indicate a preponderance of spectral energy at large scale suggests that non-local, large scale - small scale interaction is a significant spectral transfer process.

Here, we explore mechanisms for non-local transfer in drift wave turbulence. Specifically, we have focused on:

i.) induced diffusion[1], which results from the resonance between nonlinearly generated beat wave packet with a low frequency, large scale wave.

ii.) parametric subharmonic[1] instability, which results from parametric decay of strongly excited, large scale waves.

Results indicate that induced diffusion will tend to smooth high-k spectral features (due to induced diffusion in k-space). A physical model of this process, based on analogy with the well-known problem of wave propagation in random media, has been developed as well. k-space diffusion coefficients and spectral flow rates have been calculated. Regarding parametric instability, the results are similar to those of Hasegawa and Mima[2]. However, exploration of the role of non-linear broadening indicates that interaction with zonal flows, as well as 'super-harmonic' instability, can occur if $\Delta\omega_{\underline{k}}$ is large enough. Work on a wave kinetic equation encompassing all processes is in progress.

We will also report on a study of long wavelength drift wave turbulence, where $\underline{E} \times \underline{B}$ nonlinearity is non-negligible. Such a situation, which occurs in toroidal dissipative trapped electron drift wave turbulence, can lead to competing spectral flows due to different nonlinear interactions.

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Particle Simulation Method for Non-circular Toroidal Plasmas Using Non-orthogonal Curvilinear Coordinate Systems*

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A numerical method has been developed for electrostatic particle simulation of arbitrarily shaped toroidal plasmas such as axisymmetric tokamaks with non-circular cross sections. Two-dimensional non-orthogonal flux surface coordinates are generated from the numerical solution of the Grad-Shafranov equation. Using a coordinate transformation technique, interpolation and smoothing of charge densities and electric fields are made in the transformed nonorthgonal coordinates. A fast Poisson solver has been developed in which finite defference scheme for cross sectional directions and FFT for toroidal direction are employed. Time-decentered Lorentz pusher is used to integrate the momentum equation of ions where decentering is effective to eliminate the ion cyclotron limitation on time step. The Lorentz pushing is most conviniently and generally carried out in cartesian coordinates transformed back from the nonorthgonal coordinate system. The ion motion thus contains all electric and magnetic drifts including the polarization drift. Electrons are pushed in the transformed coordinates using the drift equations. The algorithm is being incorporated into the Toroidal Particle Code [1].

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Gyrokinetic particle simulation of drift and trapped particle modes in a toroidal metric*

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The gyrokinetic algorithm [1] has been implemented in the Toroidal Particle Code [2]. This code uses an (r, θ, ϕ) type coordinate system and a nonuniform radial field mesh. The gyroaveraging of the ion density and interpolated electric field is accomplished by a variant of the usual four-point method. Terms scaling as $(k_\perp \rho_i)^2$ in the Poisson equation are expanded as $\rho_i^2 \nabla_\perp^2$. The Poisson equation is inverted via iterative application of a rapid elliptic solver. Comparisons to the full dynamics method will be given, including the simulation of the toroidal drift and trapped particle modes studied previously [3].

We also discuss the observed power spectrum in previous toroidal simulation runs with a Gaussian density gradient, with or without temperature gradients. In the $\eta_e = \eta_i = 0$ case, the poloidal harmonics are strongly coupled by the θ–dependence in the Laplacian and the magnetic drifts. The strong, low frequency mode that emerges has the characteristics of a toroidicity-induced drift mode. $S(\omega)$ decays roughly as ω^{-1}, which is in rough agreement with some recent observations from TFTR. For the $\eta_e = \eta_i = 1$ case, the spectral density shows a stronger peak at low frequencies and more local behavior in r, consistent with the weaker mode coupling from radial variation of ω^*.

Additional runs employing enhanced transport diagnostics and varied η_e, η_i are underway.

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Particle Simulations in Toroidal Geometry *

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The electrostatic toroidal particle code of LeBrun[1,2] has been extended to include a magnetostatic algorithm which allows self-consistent solutions of the magnetic field. The field equations for the magnetic field are solved iteratively in toroidal geometry using Fourier expansions in the two angle coordinates and finite differencing in the radial coordinate. Comparison of a magnetostatic simulation is made with an electrostatic simulation. Extension of the code to include a Darwin model for the self-consistent fields is discussed.

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Fractal Dimensions of Asymptotic States in Plasmas

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Many plasma configurations evolve into nearly stationary asymptotic states under suitable conditions. Viewed from the dynamical systems perspective such states are attractors and this property can be studied by examining the dimensionality of the system. Given the time series of one or more physical variables we construct its state space by the time-delay embedding method and then use the correlation-sum technique [1] to determine the dimension of the attractor. If the plasma asymptotic state is a strange attractor it gives a fractal dimension and this in turn gives the minimum number of degrees of freedom in the system. We apply this technique to two cases viz., the two-stream instability and the collisionless shock. The two-stream instability is simulated with a one-dimensional electrostatic particle code and shows interesting features in the asymptotic state. After the stages of linear growth, nonlinear saturation and turbulence, the plasma evolves into an asymptotic state in which the vortices in the phase space merge into a single vortex. In this state the time-series data is taken at different space points and analyzed to determine the fractal dimension. With different embedding dimensions we get convergence to a fractional value of about 6. This implies that this system with a very large number of degrees of freedom, of the order of the number of particles, evolves into a strange attractor with fractal dimension and can be described by a small number of dynamical variables. In the case of the collisionless shock, a one-dimensional hybrid (particle ions and fluid electrons) code is used to obtain the near-stationary shock structure. Time-series data of different physical variables are taken at the upstream, within and downstream regions of the shock and these are used to determine the dimensionality of the system. The details of this analysis will be presented. The existence of a low-dimensional strange attractor in a system with many degrees of freedom yields the possibility of constructing simple models of its asymptotic states.

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CONVECTIVE MODES OF DRIFT WAVES IN TOROIDAL PLASMA SYSTEMS*

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Abstract

Drift wave patterns of plasmas in a toroidal geometry are studied. The dispersion relation was simplified, yet remained complicated enough to retain both the shear effect and the toroidal coupling. Since the dispersion relation does not depend on the toroidal angle, ϕ, the dispersion is solved in the two-dimensional space made up with minor radius and poloidal angle. This dispersion relation was previously analyzed by Chen and Cheng.[1] The dispersion relation can be reduced into second-order, partial differential equations of a hyperbolic type. The convective mode analysis of one dimension, which was originated in the 1960's, was then extended into the two-dimensional analysis. The results show that the plasma is expected to be unstable for large azimuthal mode number and that the plasma instability tends to be more stabilized for large mass ions.

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Nonlinear Theory of Flat Density Ion Temperature Gradient Toroidicity Induced Trapped Electron Modes in Hot Ion H-Mode Plasmas

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Recent experimental results from DIII-D hot ion H-mode plasmas with flat density profiles[1] indicate that the electron thermal transport exceeds the ion thermal transport in the core where the collisionality is very low. This result seems counter-intuitive based upon the common knowledge of ion temperature gradient driven turbulence theories, since the fluctuations propagating in the ion diamagnetic direction result in $\chi_i > \chi_e$, D, especially in the collisionless trapped electron regime. In this work, a nonlinear theory is developed for recently discovered flat density ion temperature gradient toroidicity induced trapped electron modes[2] propagating in the electron diamagnetic direction. This instability is predicted to be linearly unstable for $L_{Ti}/R < k_\theta \rho_s < (L_{Ti}/R)^{1/4}$. They are also found to be strongly dispersive even at these long wavelengths, thereby suggesting the importance of ion Compton scattering in the nonlinear saturation phase. The analytically calculated spectral intensity of density fluctuations obeys a very steep power law $I(k_\theta) \propto k_\theta^{-22/3}$ in the dissipative TEM regime, and a less steep decay in the collisionless TEM regime. In accordance with the trends observed in DIII-D, the predicted electron thermal diffusivity can be larger than the ion thermal diffusivity.

Acknowledgments

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Nonlinear Dynamics of Dynamo and Quasiperiodic Relaxation in RFPs*

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To date, the detailed dynamics underlying the self-generation of magnetic flux ("dynamo") in RFPs are not completely understood. To elucidate the dynamo mechanism, we study the experimentally observed[1] "sawteeth", which are believed to be consist of discrete dynamo events. Each sawtooth begins (destabilization phase) with diffusion of the current profile away from a stable state; it ends (relaxation phase) when the resultant fluctuation restores the stable current profile via the dynamo. Recently, it was shown that 3D MHD codes can model key magnetic fluctuation features of the sawteeth[2]. We use a similar code for our study[3]. The results are diagnosed and interpreted by a new energy diagnostic, which enables us to study the power transfer between groups of modes. Thus, we are able to identify the path taken in Fourier space by the poloidal magnetic field energy, as it is converted to axial magnetic field energy during a dynamo event.

We have isolated single nonlinear relaxation events in a highly damped system, and produced quasiperiodic relaxation in a more dynamic system (higher S and larger aspect ratio). The $m = 0$ modes are crucial to produce the proper dynamics, although the $m = 1$ modes can reverse the axial field by themselves. The $m = 0$ modes nonlinearly enhance the $m = 1$ dynamo effect. They increase the poloidal power flux to the $m = 1$ modes resonant near the axis, nonlinearly transfer the energy to $m = 1$ modes resonant near the reversal surface, and help convert this energy to the axial magnetic field. The quasilinear effect of the $m = 0$ modes is, however, anti-dynamo.

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SHERWOOD THEORY MEETING, WILLIAMSBURG, 23-25 APRIL, 1990

On Standard Forms for Transport Equations and Fluxes—Part II*

(3/2 vs. 5/2 again?)

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Quasilinear expressions for anomalous particle and energy fluxes arising from electrostatic plasma turbulence in a tokamak are reviewed yet again. Further clarifications are made, and the position taken in a previous report[1] is modified. There, the total energy flux, Q_j, and the conductive heat heat flux, q_j, were correctly defined, and the *anomalous* Q_j was correctly calculated. It was shown that the anomalous energy transport can be correctly described by $\nabla \cdot Q_j^*$, where $Q_j^* = \frac{3}{5} Q_j$, with all remaining source terms such as $\langle \tilde{p}_j \nabla \cdot \tilde{V}_j \rangle$ cancelling. Here, a revised discussion is given of the identification of the anomalous conductive flux, q_j, in which the distinction between Q_j and Q_j^* is reconsidered. It is shown that there is more than one consistent way to define q_j.

Transport calculations involving only theoretical electrostatic turbulent fluxes are unaffected by these distinctions since Q_j or Q_j^*, rather than q_j, is the quantity conveniently calculated in the theory. However, an ambiguity remains in experimental transport analysis[2] owing to the presence in the energy equation of source terms such as $p_j \nabla \cdot V_j$ or $\langle \tilde{p}_j \nabla \cdot \tilde{V}_j \rangle$, if the flow velocity V_j is inferred from the measured particle flux $\Gamma_j = n_j V_j$

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STOCHASTIC MAGNETIC FIELDS AND ELECTRON HEAT TRANSPORT INDUCED BY NEOCLASSICAL MHD INSTABILITIES*

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Within the resistive MHD plasma model, magnetic islands can be generated when either the q and/or pressure profiles violate stability thresholds. For profiles and parameters typical of current high-temperature plasma regimes, this does not generally result in large enough islands to cause significant overlap and stochastic regions, except on a transient basis. However, within the neoclassical MHD model, new free energy sources are present, such as the fluctuating bootstrap current, which can generate overlapping steady-state island chains in high temperature collisionless regimes. The resulting growth of multiple-helicity islands leads to regions of stochastic magnetic field and the level contours of magnetic flux can develop a complex topology and connect inner and outer radial regions. As previously recognized, the perpendicular electron conductivity in the presence of such field structures is enhanced by the random radial component of magnetic field coupled with the high parallel electron conductivity. An analytic theory[1] of the influence of neoclassical pressure-gradient-driven turbulence on χ_e has indicated a scaling similar to that of resistive turbulence. In this talk, examples of neoclassical MHD island generation will be presented using results from a nonlinear multiple-helicity 3-D initial value code which solves an averaged set of neoclassical MHD equations in cylindrical geometry. Profile and parameter dependences will be discussed and comparisons made with the analytic theory.

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HIGH FREQUENCY SURFACE HELICITY INJECTION IN AXISYMMETRIC TOROIDS WITH MOVING PLASMA BOUNDARIES

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Abstract

Recently, it has been argued that the negative results of many F-θ experiments on helicity injection may be due to effects of a moving plasma boundary. We have reexamined the possibility of helicity injection at a plasma surface using oscillating fields around the ion-cyclotron frequency. We find that ion-inertial effects and ion-dissipation can lead to a significant helicity injection at the surface. Estimates of the surface helicity injection indicate that steady state current in a tokamak may be driven efficiently using this method.

Three-dimensional Visualization of the Reconnection and Tilting of a Compact Torus in the Refueling of a Tokamak *

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We are interested in studying the feasibility of refueling a tokamak by injecting plasma in the form of a succession of compact toruses. The simulation is done by applying the 3D resistive MHD code TEMCO to follow the evolution of a compact torus as it undergoes tilting and field line reconnection. Since the compact torus carries energy and magnetic flux, in addition to the plasma, it can also be used to heat the tokamak and provide current drive. The output from TEMCO consists of 8 MHD scalar fields each defined on a 3D domain. It is of such bulk that we have resorted to 3D visualization techniques to be able to see the modeled dynamics of the refueling process. We use both multiple cross-sectional mappings as well as volume rendering techniques to allow us to see what is actually happening. Video animations of these simulations are being prepared for this presentation.

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Self-Stability of Mercier modes in a Heliac

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Fusion devices operating in the second stability regime are very attractive since it increases the amount of plasma pressure contained in the device. Second stability regime has been predicted theoretically for tokamaks and stellarators; moreover self-stabilization has been observed experimentally in the first operation of the ATF device [*J. Harris, et al., Phys. Rev. Lett. 1989*]

The Flexible Heliac TJ-II [*The TJ-II Team, Fus. Tech. 1990*] under construction in Spain is characterized by a high degree of flexibility, i. e. by changing the ratio of currents in its two central coils, different magnetic configurations can be achieved with a wide range of parameters ($0.22 \leq \iota/4 \leq 0.628$, -1%.≤magnetic well ≤6%,). A study of finite beta equilibria and stability to Mercier modes for a set of TJ-II configurations showing "first region" behavior, has been recently completed [*A. Varias et al., submitted to Nucl. Fus.*].

We have also obtained another family of configurations with rotational transform/period ≈ 0.3, that has shown self-stabilization behavior to ideal Mercier modes [*C. Alejaldre, et al. 1st International Toki Conference, Dec.1989*]. In this work a detailed description of the mechanism responsible for that stabilization is presented.

Review of Evidence for Magnetic - Turbulence - Induced Transport

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Modern theories of magnetic-turbulence-induced (MTI) transport typically find electron thermal diffusivities exceeding particle and ion thermal diffusivities by at least one order of magnitude. Energetic electron transport in the few-100 keV range, due to this mechanism, should be faster yet. Impurity and momentum transport would presumably be comparable to particle and ion heat transport.

In this poster we review the experimental evidence that has previously been taken as indication of MTI transport. Modern measurements show that ion thermal diffusivity, and particle, impurity, and momentum diffusivities in almost all regimes, are comparable to electron thermal diffusivity. The limited (but diverting) contrary evidence from DIII-D and JET will be discussed. The evidence from TFTR that total electron heat transport can be as low as $2.5\Gamma T_e$ speaks against MTI transport as well.

Energetic electrons have been used as a diagnostic for MTI transport. We review the evidence from Alcator A, PLT, and ASDEX. In the case of Alcator A we find that the distortion of the energetic electron tail can be explained by transport due to magnetic field ripple. In the case of PLT we find that the energetic-electron heat-pulse-propagation is comparable to the standard soft-X-ray heat-pulse-propagation on similar devices. The evidence on energetic electron transport in ASDEX vs. q_a and P_{heat} can be used in an argument against the importance of MTI transport even in NBI-heated regimes. Finally, we observe that the success of lower-hybrid-heating and lower-hybrid-current-drive indicates that MTI transport is not important in such regimes.

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SHERWOOD THEORY MEETING 1990

Nonlinear Instability, Chaos, and the Three-Wave Interaction*

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Linearly stable equilibria of Hamiltonian systems are conjectured to be generically unstable if δ^2F, the second variation of the free energy functional, is indefinite.[1,2] Such a system is said to possess a negative energy mode, and explosive instability can occur via resonant wave-wave coupling. An initially non-resonant set of waves may eventually become resonant via chaotic transport in phase space. We demonstrate this for the three-wave interaction in a simple counterstreaming ion configuration. A four-dimensional symplectic mapping is used to follow the evolution of the wave, and time scales for the instability are determined.

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Fast Wave Current Drive Calculations for ITER Using the ORION Code*

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ORION is a 2-D finite difference ICRF code which solves the wave equation in non-circular, straight tokamak geometry. 3-D field structures are obtained by summing k_z (i.e. toroidal) modes. Cyclotron damping of ion species and alphas as well as Landau damping and TTMP on electrons is included. An analytic current drive model developed by D. Ehst has been incorporated. The model, obtained by fitting code results of Karney and Fisch, includes trapped particle effects. Calculations have been carried out for 20 MHz and 60 MHz ITER scenarios. Presented here are 20 MHz results for the integral in-blanket antenna design with up to 60 elements. Since damping is relatively weak, eigenmode effects are very important. The current drive figure of merit, γ, and loading resistance per unit length per strap, R_L, are sensitively dependent on density. We easily find cases in which $\gamma \sim 0.45$ and $R_L \sim 2\Omega/m$. By careful matching of the $k_{\|}$ spectrum to the eigenmode structure we have obtained γ up to 0.6 and R_L up to $17\Omega/m$. The principle sources of possible error in these calculations are: (1) the straight cylindrical model — variations of $k_{\|}$ across the plasma cross section are not modeled accurately; (2) the neglect of relativistic effects; and (3) the presence of a shear Alfven resonance on the inside edge (i.e. small R_T) of the plasma which causes small scale structure is not resolved by the code, but no effect on absorption is seen.

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Equilibrium Beta Limits in Heliotron-E due to Magnetic Island Overlap

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We investigate the formation of magnetic islands due to finite beta effects in the Heliotron-E configuration. The island overlap criterion is used to obtain an equilibrium beta limit. The magnetic island widths are computed using the analytic calculation of Hegna and Bhattacharjee,[1] who extended an earlier calculation due to Cary and Kotschenreuther.[2] The magnetic island width depends on the local resistive interchange properties (measured by the D_R criterion of Glasser, et al.[3]) of the associated integrable magnetic configuration. The island widths are computed numerically by using the STEP code, recently modified by Nakamura, et al. to evaluate D_R.[4] The calculations indicate that as beta exceeds 2%, resistive interchange effects produce overlapping magnetic islands. Earlier experimental results on beta-driven internal disruptions are revisited. It is argued that magnetic island overlap in the equilibrium is responsible for the observed internal disruptions at $\beta \sim 2\%$ and the flattening of the pressure profile.

This work is supported by the U. S. Department of Energy Grant No. DE-FG02-86ER53222.

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Current Density Profile Evolution and Steady State Configurations*

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We investigate the important question of the time evolution of the current density profile in toroidal devices, and the nature of the steady states associated with the assumed transport. Considering measurements of the safety factor $q(r)$ carried out on the circular TEXTOR [1] device for a wide range of edge values q_a, combined with an examination of the equilibrium fitting procedure used to analyze magnetic data from the elongated D-III-D tokamak [2], we postulate the existence of steady state q profiles with central q_0 a geometry-independent (weak) function of q_a and flux surface averaged current density j of the form $j \propto (1 - V/V_a)^{\gamma(q_a)}$, V being the volume enclosed by a flux surface. For a given q_a, the exponent γ is significantly smaller for elongated outer flux surfaces with triangularity than for circular boundaries. To be consistent with these profiles and with the observed "neoclassical" relationship between total plasma current and loop voltage, we first propose adding to the usual Ohm's law in general geometry a phenomenological term $V_* B_p$, where B_p represents an average poloidal magnetic field and the effective velocity V_* is strongly positive in the inner part of a discharge but negative in the outer portion.

Although adequate for steady state situations, this modified Ohm's law is still incomplete with respect to the temporal evolution of the current density. The $V_* B_p$ term acts to cancel strong effects associated with the spatial gradient of the trapping contribution to neoclassical resistivity, and experimental observations of the decrease in q_0 during current flat-top in beam-heated JET [3] discharges ($T_e \sim 8\text{keV}, a \sim 1.1$ m) and ohmic TEXTOR [1] discharges ($T_e \sim 1\text{keV}, a \sim .4$ m) cannot be made consistent with the classical resistive scaling $\tau_c \sim l^2 T_e^{3/2}$, with l an effective length scale. Our solution is to propose an additional modification to Ohm's law of the form $(\eta_{AN} j + V_{**} B_p)$, with an anomalous resistivity η_{AN} that is only weakly dependent on temperature and with V_{**} defined in such a way that the combination $(\eta_{AN} j + V_{**} B_p)$ vanishes for the steady state profiles described previously.

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SHERWOOD THEORY MEETING 1990

The MFE Database: Content and Access*

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A profile oriented database for storing experimental data from a variety of toroidal magnetic confinement devices has been established. The fundamental purpose of this database is to make experimental results from different devices widely available to the MFE community. The current implementation is a fully relational model consisting of twelve relations. The principal relation is the **discharges** table, which is keyed by the experimental device name and a shot number. The remaining relations contain the detailed information required to give a complete description of the discharge.

During the past year, over 800 shots from TFTR, PDX, PLT, T-10, JT-60, and TEXT have been placed in the database. A variety of discharge conditions is represented, ranging from single time slice ohmic discharges to multiple time slice ECH discharges. Included with most data sets is a reference to a published paper or report that describes the experiment being performed when the data was taken.

The database is currently implemented under INGRES† on a VAX that is on the MFE network. At this time, the only way to access the data is by obtaining an account on this VAX, logging in and running INGRES. The VAX is currently available via MFENET, ESNET, INTERNET and TELNET. The procedure is for the user to use SQL[1] (Structured Query Language) to access the data. Once the user determines what data are to be analyzed they can be retrieved and sent over the network to the user's local site for analysis. Future plans include providing a LOCUS[2] front end for viewing the data on any generic graphics terminal and possibly other user friendly interfaces such as HyperCard for Macintosh users. Additional information can be obtained via electronic mail from **mfedb@uta** (MFENET and ESNET) and **mfedb@fusion.ph.utexas.edu** (INTERNET and TELNET).

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* Supported by USDOE Grant DE-FG05-88ER53266

† INGRES is a trademark of Relational Technology Inc.

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ANALYTIC THEORY OF CURRENT DRIVE BY AN EXACT SOLUTION OF KINETIC EQUATION

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The phenomenon of current drive under the action of radio frequency travelling waves into a tokamak is analytically studied by solving the two dimensional Fokker-Planck equation first treated by Fisch. The runaway rate, the number of runaway electrons, the electric current density and power density are obtained analytically and are compared with the results of one dimensional analytic treatment.

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An Explanation for New Cold Fusion in Metal Electrodes - A New Quantum Effect in Nuclear Fusion

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In dense metal electrodes every pair of reacting nuclei in collision and fusion processes is subjected to the action of strong external fields of surrounding charged particles. Considering such action, the general formulae of fusion cross-section were derived from quantum mechanics. These formulae show that there is a new quantum effect in nuclear fusion, i.e. the external fields have an effect on the fusion processes. When the external fields tend to zero or reacting nuclei are at high kinetic energy, these formulae can be simplified to Gamow formula of fusion cross-section. They can be used to qualitatively explain the results of new cold fusion observed in Fleischmann's experiments. It is shown in principle that the cold fusion generated in metal electrodes in Fleischmann's experiments is not electrochemically induced, it is induced by the action of external fields formed from the ions in metal lattice, i.e. as a result of the action of the new quantum effect. It is first found that the principle of the new cold fusion generated in metal electrodes is the same as that of those abnormal fusion phenomena observed in dense, low temperature ($T < 10^5$ K) plasmas. A new fusion mechanism in metal electrodes is first presented. It shows that there are various possible ways to raise the fusion rate in metal electrodes. These conclusions have yet to be verified by further experiments in the near future.

COHERENT STRUCTURES IN η_i-MODE TURBULENCE

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Numerical simulations[1,2] of the ion temperature gradient driven mode (η_i-mode) show that long lived, large scale coherent structures exist and play an important role in the study of the anomalous transport. In this work, we find the stationary solutions of the nonlinear equations describing the dynamics of η_i-mode. The simplest solution is found to be a dipolar vortex in shearless case. In the presence of the magnetic shear, we find a modified dipolar vortex solution through perturbation theory.

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Sherwood Abstract

Variational Theory of Neutral Particle Transport*

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The kinetic theory of neutral particles in a hot plasma, including the effects of impact ionization, recombination and charge exchange collisions, is studied analytically. Previous analytical investigations (by Connor[1], for example) depend upon various simplifications, such as the constancy of the charge exchange cross-section in energy. The present approach is complementary: it simplifies by restricting attention to regimes in which the mean-free path for charge exchange, λ_x, is short, but allows for accurate charge-exchange operators, general energy dependence and three-dimensional geometry. An H-theorem is constructed, as well as a fully general variational principle for the neutral entropy production. In the short-λ_x regime, the neutral kinetic equation is analyzed by Chapman-Enskog theory. The corresponding version of the variational entropy production is used, with appropriate trial functions, to compute the neutral transport coefficients, describing particle and heat flow, in three dimensions.

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THE EXACT AND DRIFT HAMILTONIAN

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We examine the relationship between the exact Hamiltonian and the drift Hamiltonian of charged particles in electric and magnetic fields. The exact Hamiltonian has six variables, which can be the position vector $\vec{X}$ and the velocity vector $\vec{V}$. The drift Hamiltonian has four variables, which can be the position vector $\vec{X}$ and the velocity along the magnetic field $V_{\parallel}$. These variables are not canonical coordinates. We derived new forms of both Hamiltonians in terms of canonical coordinates. The four canonical variables of the exact Hamiltonian are the same as those of the drift Hamiltonian. The other two are: the particle momentum perpendicular to the field lines in the magnetic surfaces, and the momentum perpendicular to the magnetic surfaces. The average over these two momenta gives the drift Hamiltonian. The feature that both exact and drift Hamiltonians are in the same coordinates simplifies the comparisons between the exact and drift trajectories. We are now carrying out numerical calculations to assess the faithfulness of the drift trajectories to the true trajectories.

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MAXIMUM ENTROPY EQUILIBRIA OF A NONNEUTRAL GUIDING-CENTER PLASMA [1]

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Thermal equilibria are constructed for a two-dimensional guiding-center model of a magnetically confined, nonneutral plasma column in a cylindrical trap. The entropy is maximized for fixed particle number, electrostatic energy, and canonical angular momentum. This leads to confined equilibria which may have formally negative temperatures. The associated density (vorticity) distributions are not circularly symmetric if the energy and/or angular momentum is sufficiently large. These are stable dynamical equilibria, in which density is constant on streamlines in a rotating frame. The breaking of rotational symmetry, which is analogous to a second-order phase transition, is analyzed by means of bifurcation theory of a Vlasov description. The results are in close agreement with Monte Carlo simulations of microcanonical ensembles of discrete guiding centers. Such guiding-center thermal equilibria may describe the result of (nonideal) turbulent interactions of diocotron waves or shear-flow instabilities, when these are sufficiently violent and occur on time scales such that the associated $\vec{E} \times \vec{B}$ motion is decoupled from velocity-space degrees of freedom. Computational schemes are presented for finding these equilibria and describing fluctuations around them.

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Numerical Computations of Resistive MHD Instabilities*

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A resistive MHD stability code, (NOVA-R), was developed for axisymmetric toroidal systems. In order to accurately calculate resistive instabilities for resistivity in the range of fusion reactors, it is essential to overcome the problem of numerical errors associated with the fast magnetosonic wave. An optimal formulation of the eigenmode equations has been carefully chosen for the NOVA-R code on the basis of minimizing the numerical error due to fast wave terms by accurately resolving the continuum spectrum of the ideal MHD operator. Our formulation reduces the resistive MHD stability equations into three coupled second order equations in the minor radius. One of the three equations recovers the identical formulation of the NOVA [1] code in the ideal limit. The full set of linearized resistive MHD equations are solved everywhere in the plasma.

In cylindrical cases, we have demonstrated that the NOVA-RC code can produce accurate results for resistivity as low as 10^{-30}. For axisymmetric toroidal plasmas we have demonstrated the accuracy of the NOVA-R code by recovering ideal results in the $\eta \rightarrow 0$ limit, and cylindrical resistive results in the $a/R \rightarrow 0$ limit. Δ' analysis was performed using the eigenfunctions computed by the NOVA-R code and resulted in excellent agreement with the resistive PEST results [2] for zero beta equilibria.

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1990 INTERNATIONAL SHERWOOD THEORY MEETING

GUIDING CENTER STOCHASTICITY IN A TOKAMAK.*

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We are studying the guiding center motion of charged particles interacting with electrostatic waves in a tokamak. This motion is described by a time dependent Hamiltonian in a four dimensional phase space composed of the guiding center's three position coordinates and its parallel velocity (along the magnetic field). The motion of the guiding center can become stochastic when the wave amplitudes exceed a threshold value. The stochastic motion of guiding centers through prescribed waves has been studied previously for two limiting cases: motion along the magnetic field with no drifts, and drift motion without parallel wave fields. In each of these cases one can view the dynamics in a two dimensional surface of section and the relevant diffusive process is one dimensional. We are generalizing these approaches by considering the dynamics in four dimensions thereby obtaining diffusion in both the guiding center parallel velocity and radial position. The example being considered is that of super-thermal electrons during lower-hybrid current drive. We show that the dynamics is described by two coupled two dimensional phase planes, one for the parallel motion and the other for the perpendicular drift motion. The perpendicular motion is sensitive to the parallel dynamics such that both motions become stochastic when the overlap criteria is satisfied in the parallel phase plane. The parallel motion depends on the drift motion primarily because of the shear of the equilibrium magnetic field. This leads to Arnold diffusion which persists even in the absence of of widespread stochasticity.

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Transport Simulations of TFTR Experiments to Test Theoretical Models for χ_e and χ_i *

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The $1\frac{1}{2}$-d BALDUR transport code is being used to test a variety of theoretical models for χ_e and χ_i against data from ohmic and neutral beam heated experiments on TFTR. Simulations include cases with ion temperature profile measurements, so that models for both χ_e and χ_i can be evaluated. Simulations include a Kadomtsev sawtooth model, where necessary, and radiation profiles from experiment. Theoretical models from the Ross report[1] are being tested against this data base, including the multiple mode model (MMM) proposed by Singer[2], using the new Carreras-Diamond model for resistive ballooning losses[3], and the profile consistent drift wave model (PCDW)[4]. Simulation results are compared to TFTR measurements.

MMM particle transport works well for ohmic and l-mode density profile prediction, but underestimates transport for TFTR supershot. MMM successfully predicts the electron temperature profile for the ohmic cases, but overestimates both electron and ion losses in the supershot case. Ion temperature profiles are predicted to be broader than observed for both PCDW and MMM. Electron temperature profiles and ion temperature profiles are in good agreement with experiment for simulations using PCDW. Modification of MMM parameters to give agreement with TFTR data and results with a TFTR L-mode case will be discussed.

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PARTICLE TRANSPORT AND FUELING ISSUES FOR DT DIVERTED PLASMAS*

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The particle density profile in the plasma core and scrape-off regions is expected to impact performance characteristics in many ways. Fuel particle profiles that are strongly peaked in the core are expected to increase fusion power production, improve energy confinement characteristics, and modify the pressure profile, beta limit, and sawtooth activity. Higher density in the scrape-off region reduces erosion of the divertor collector and walls by reducing the average energy per particle. The density at the boundary between core and scrape-off regions influences the density limit and L-H transition threshold. Fuel particle fluxes are expected to influence the fluxes of impurities and helium ash. The tritium fueling profile, in combination with recycling, determines the fractional burn-up of tritium, and therefore fuel processing requirements and tritium safety. The relationships between these various criteria are examined in the context of varying combinations of neutral gas and pellet fueling in the presence of particle recycle from the walls and divertor region. Because of significant uncertainties in transport effects as well as other operational criteria, early DT machines such as CIT and ITER should include very flexible fueling systems to determine experimentally the more optimal operating regimes.

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IMPROVED ANALYTIC EQUILIBRIUM FOR A FIELD REVERSED CONFIGURATION

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The Solov'ev equilibrium[1] commonly called an elongated Hill's has had a long and useful history as a simple analytic equilibrium for a field reversed configuration (FRC). However this equilibrium, which only describes the region inside the separatrix, is not consistent with the external magnetic field produced by a straight coil. This leads to significant differences between the Hill's vortex and a real equilibrium which has, e.g. a straighter, less elliptical separatrix boundary near the midplane, and somewhat more elongated flux surfaces near the midplane. These differences may have a significant impact upon both stability and transport characteristics. An improved analytic equilibrium has been constructed which includes a current free external field region, and an internal region. Like the Hill's vortex equilibrium, the pressure is assumed to vary linearly with the flux function. The internal and external solutions are matched so as to satisfy three conditions: 1) force balance at the separatrix-midplane; 2) the average beta condition (which governs the axial force balance); and 3) the shape of the separatrix of the internal and external solutions are matched to order z^2 at the separatrix. The properties of this equilibrium are developed and its implications on transport and stability are examined.

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Determination of the Energy Confinement Time in a Slowly Evolving Plasma

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An accurate determination of the energy confinement time in an evolving plasma is difficult due to the fact that experimental time traces (W, ψ, etc.) have to be differentiated. In this work we present a statistically based method which avoids differentiation of noisy data by assuming that the energy confinement time has a known functional form with free parameters that may be adjusted in a least squares sense. Using this method, we have found that the energy confinement time for many (H–mode, constant I_p) DIII–D discharges may be assumed constant during the initial, ELM-free phase of neutral beam heating. Analysis of the parameter and intrinsic curvature effects arrays associated with nonlinear least squares fitting allows us to conclude that models with the energy confinement time proportional to the plasma energy raised to some power are not acceptable during the same discharge period. It is shown that under favorable conditions the energy confinement time may be determined with a relative error of approximately ten percent.

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Simulation of High Energy Electrons in the Reversed Field Pinch *

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High energy electrons are observed in the edge of the Reversed Field Pinch (RFP). The observations show an approximately undirectional flow of these electrons along the magnetic field. Although their density is small compared to the thermal electron density, they are responsible for the major part of the current near the edge.

We simulate the high energy electrons by adding a gyro kinetic electron species, treated by particle in cell techniques, to the DEBS code. This DEBS code is a 3D resistive MHD code which includes hall terms. The dynamo fluctuations and the mean-field predicted by DEBS are used to move the kinetic electrons. The predicted kinetic electron current is fed back to the MHD code and is used to calculate the fields, making the loop self consistent.

We will present the calculated properties of test particle electrons in the edge region and elsewhere in the plasma. The model for coupling this electron current into the MHD fluctuations will be described.

* Work performed under the auspices of the USDOE

Radiative Decay of ∇T_e Drift Wave Monopole Vortices*

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The electron temperature gradient $\eta_e = \partial_x \ell n\, T_e / \partial_x \ell n\, N_e$ introduces KdV type nonlinearity in the equation that describes nonlinear drift waves. This occurs via the long wave speed $u = v_{de}(1 - \varepsilon\eta_e x - \eta_e\varphi)$ where $\varphi = e\Phi/T_e$ and $\varepsilon = \rho_s/L_N$. Because of this nonlinearity the dipole vortex is split into monopoles as shown by Su *et al.*[1] The monopoles thus produced cannot localize sufficiently to avoid coupling to propagating drift waves on the high temperature side of the vortex. The matching condition on the exterior ($k|x| > 1$) of the vortex to the drift wave, requires $1/k < |x| < k^2/\varepsilon\eta_e$ which implies $k \gtrsim \varepsilon^{1/3}$ with the turning point at $x_T = \rho_s/\varepsilon^{1/3}$. A monopole of amplitude φ_{mp} couples to outgoing drift waves with amplitude $\varphi_{mp} \exp(-L_{Te}\, k^3/\rho_s)$ where $k = (1 - v_d/u)^{1/2}$. We calculate the drift wave radiation from monopole vortices and compare with simulations. The ordering $k \sim \varepsilon^{1/3}$ is also required to make the KdV nonlinearity comparable to the Hasegawa-Mima nonlinearity.

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

Saturation Dynamics and Spectrum of Trapped Particle Drift Instabilties Using 3D Gyrokinetic Simulation Models

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ABSTRACT

A three dimensional electrostatic particle simulation model which treats the electrons as drift kinetic and follows the gyrophase-averaged ion guiding centers has been extended to include, in addition to the ExB drifts, the curvature and grad-B drifts of the particles as well as the mirroring effects parallel to the magnetic field. In cylindrical geometry with rotational transform and radial toroidal field variation, the model produces the correct trapped particle behavior. Results of drift wave instabilities driven by the trapped electrons reveal a ballooning type of mode structure with radial localization towards the outer edge of the torus. The linear growth rates and real freqency of the instability are in reasonable agreement with detailed linear analysis of these instabilities[1,2]. Saturation occurs principally through quasilinear modification of the ambient gradient as well as mode coupling effects. Test particle measurements of the particle and heat flux are made and these are compared with the quasilinear expressions for the transport coefficients using the mode spectrum obtained from the simulation at saturation. The results indicate that the heat fluxes are a factor of 5-6 times the particle fluxes for the case with a finite electron temperature and density gradients. Further work is in progress including ion thermal gradients. The results of these simulations are compared with two models which use a simplified electron response. In the first model, the electrons are broken into circulating and trapped populations. The circulating electrons are treated as adiabatic and the trapped electrons are evolved using a bounce-averaged drift. In the second model, a partially-linearized[3] approach is used to linearize the electric field response. This model reduces the particle requirements and can assess the role of various nonlinearities (ExB, wave-particle resonances,etc) on the transport.

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Minimization of Resistive Flux Loss During Current Rise *

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It is of interest to reduce $V{\cdot}s$ consumption during current rise in order, e.g., to make more available for the current flat-top phase, or simply to reduce current-swing requirements on the PF system. Resistive flux consumption depends in a complicated way on plasma parameters and operational scenarios. In order to calibrate such "knobs", a database of current-rise simulations for ITER parameters using the Tokamak Simulation Code (TSC)[1] has been constructed. The database spans a range of current-rise times and scenarios, plasma densities and Z_{eff} scenarios. Linear regression analyses of the dependence of the (Faraday) dimensionless resistive flux loss coefficient

$$C^F_{res} \equiv \int_0^t dt' \, V_{loop}(t')/(\mu_0 R_0 I_p)$$

on these factors have been carried out and used to predict conditions under which it will be minimized. Both linear and power-law models were investigated. The results are consistent with experimental observations[2] that

$$C^P_{res} \equiv C^F_{res} + (h_i - l_i)/2 \geq 0.40$$

(C^P_{res} is the "Poynting" loss coefficient), and indicate that the proper strategy for minimizing resistive flux loss is rapid current rise, low Z_{eff}, and low density.

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THREE DIMENSIONAL FIELD LINES IN A TOKAMAK WITH A DIVERTOR — A CHAOTIC SCATTERING PROBLEM*

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A study has been made of magnetic field lines in a model for a tokamak with a divertor in the presence of three dimensional perturbations. These perturbations take the form of toroidal field ripple or MHD mode activity. Since there are field lines connected to the divertor plate, the lines fall into three categories: those on KAM surfaces; those which are chaotic but bounded by KAM surfaces; and those which exhibit *chaotic scattering.* This problem is closely related to the three dimensional reconnection of plasmoids in the solar corona or in the magnetosphere.[1] The field lines of the third class are all connected to the divertor plate and chaotic scattering manifests itself as a *fractal* dependence of the length of the field line, as well as the exit position on the divertor plate, on the initial position on the divertor plate. We will consider the possible connection of these phenomna with the L- to H-mode transition.

1. Y.-T. Lau and J. M. Finn, "Three Dimensional Kinematic Reconnection of Plasmoids," in preparation.

* Work supported by DOE.

About Possibility of Divertor Configuration Creating in T-3M Tokamak*

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There were numerical simulation operation scenarios in T-3M tokamak in which the plasma transients from limiter regime to divertor one and has two X-points inside the vacuum vessel that are symmetric relative equatorial plane. There was shown the current quantities in poloidal coils for two cases — when this transient occurred at the constant plasma current and the regime of its decreasing. The results of this work can be useful in designing tokamaks with poloidal divertors, by means of modification of existing systems.

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Size and Field Scaling for Dimensionally Similar Tokamak Discharges

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The tokamak operates in a variety of confinement regimes suggesting there may be several transport mechanisms. The detailed parameter dependence of each is likely to be very complicated. However, it can be shown that all magnetized plasma diffusion mechanisms can be divided into the extremes of gyro-Bohm (gB) or Bohm (B) types, depending on their scaling with ion gyroradius relative to the minor radius ρ_s/a [$\rho_s = c_s/\Omega$, $c_s = \sqrt{T/M_i}$, $\Omega = eB/M_i c$]. These correspond to turbulent (or classical) diffusion processes with short or long step sizes scaled to ρ_s or a respectively. The local diffusivity and energy loss rates can be written as $D_{gB} = (c_s/a) \cdot \rho_s^2 F_{gB}$ or $D_B = c_s \rho_s F_B$, and $\tau_{gB}^{-1} = B(\rho_s/a)^3 \bar{F}_{gB}$ or $\tau_B^{-1} = B(\rho_s/a)^2 \bar{F}_B$. The form factors ($F$) are possibly complicated functions of geometric parameters (safety factor q, aspect ratio R/a, elongation b/a), profile and atomic parameters (L/a where L is any plasma gradient length, A, Z_{eff}), and the plasma parameters collisionality ($\nu_* \propto \nu a/c_s$) and β (or β/β_{crit} where $\beta_{crit} \propto a/Rq$). [The Debye length $\lambda_D/a \simeq 0$ is not considered.] Discharges with all these dimensionless parameters identically the same can be called "dimensionally similar."

Existing tokamaks and proposed ignition tokamaks are dimensionally similar and differ only in their ρ_s/a values. If either gyro-Bohm or Bohm scaling dominates, then we have a powerful tool for size (a) and field (B) scaling existing discharges to ignition. For dimensionally similar discharges, it is easy to show that $\tau_{gB} \propto Ba^{5/2}$, $[n(0)T(0)\tau]_{gB} \propto B^3 a^{5/2} \propto I^3/a^{1/2}$ with $P \propto Ba^{1/2}$ or $\tau_B \propto B^{1/3}a^{5/3}$, $[n(0)T(0)\tau]_B \propto B^{7/3}a^{5/3} \propto I^{7/3}a^{-2/3}$ with $P_B \propto B^{5/3}a^{4/3}$. In addition, $n \propto B^{4/3}a^{-1/3}$, $T \propto B^{2/3}a^{1/3}$, and $\rho_s/a \propto B^{-2/3}a^{-5/6}$. $n/n_{limit} \propto B^{1/3}a^{2/3}$. Using these scalings, representative DIII–D H–mode discharges with low q, high β/β_{crit}, and largest $n(0)T(0)\tau$ are mapped to ignition with minimal increases in B and/or a.

Unfortunately, the experimental distinction between gyro-Bohm and Bohm scaling is not entirely clear. Ignoring the likely weak dependence on ν_* and β/β_{crit}, then $\tau_{gB} \propto B^{4/5}a^3n^{3/5}P^{-3/5}$ and $\tau_B \propto B^{1/2}a^{5/2}n^{1/2}P^{-1/2}$ at fixed a/R and q. For comparison, Goldston L–mode scaling is $\tau_L \propto Ba^{2.4}n^{+0}P^{-1/2}$. A statistical B- and a-scaling study with constant a/R, q, ν_*, β/β_{crit} slices of the global data base may distinguish between $\tau_{gB} \propto Ba^{5/2}$ and $\tau_B \propto B^{1/3}a^{5/3}$. Precise B-scaling experiments on DIII–D are planned and DIII–D–JET a-scaling comparisons are under discussion.†

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*Also at University of California at San Diego, San Diego, California.

†J.G. Cordey *et al.* (independent work in progress).

Sherwood Meeting, April 23-25, 1990
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Stability Properties of the ATF Torsatron During Entry to the Second Stability Region*

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Entry into the second stability regime has been achieved in the ATF torsatron.[1] In this regime the plasma is stable to ideal modes and has a beta value higher than that where ideal instability is seen. Since this second stability region may be unstable to resistive modes, resistive stability may be used as a signature of entry. A reduction in the level of resistive instability signals entry into the region. The resistive MHD model as implemented in the computer code FAR[2] can reproduce the reduction in magnetic field perturbation strength seen experimentally on ATF as β_0 is increased from $\sim 1\%$ to $\sim 2\%$.[3] These nonlinear evolutions started with equilibria which were ideally stable. The nature of this resistive instability has been studied using both linear calculations with the full resistive equations and calculations using a large n (toroidal wave number) limit of the resistive equations. The latter approach allows the global stability behavior to be studied since the flux surfaces decouple. This results in equations in which the plasma radius appears as a constant parameter. These equations very closely reproduce the results of the full equations when relevant comparisons are made. They may thus be used reliably to study the stability behavior. It has been found that the instability has a strong ballooning behavior in the plasma interior but has a resistive interchange character near the edge. The stabilization as beta is increased results from the development of a magnetic well as the plasma magnetic axis shifts outward. The appearance of any magnetic well is sufficient to stabilize the pure resistive interchange. A much larger well is required, however, to stabilize the interior mode with the strong ballooning character. Details of the above will be presented.

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

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[2] L. A. Charltron, J. A. Holmes, V. E. Lynch, and B. A. Carreras, "Compressible Linear and Nonlinear Resistive MHD Calculations in Toroidal Geometry," to be published in J. of Comput. Phys.

[3] L. A. Charlton, J.-N. Leboeuf, B. A. Carreras, and V. E. Lynch, B.A.P.S. **34** (1989) 2059.

Relativistic Standard Map*

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The acceleration and diffusion of particles in the infinite, discrete wave spectrum $\sum_n E \sin k(x - n\, v_0 t)$ given by the Standard Map is well known. However, for accelerator modes they accelerate quickly and even for the diffusion in the long-time limit the waves produce relativistic particles. Using relativistic equations for the same model gives a two parameter map with $\beta = v_0/c = \omega_0/k_0 c \gtrless 1$ and $K = \Delta p/mv_0 = 2\pi e(E/k_0)/mv_0^2$. The relativistic standard map is

$$P_{n+1} = P_n - \frac{K}{2\pi} \sin(2\pi X_n)$$

$$X_{n+1} = X_n + \frac{P_{n+1}}{\sqrt{1 + (2\pi\,\beta\, P_{n+1})^2}}$$

which reduces to the standard map for $\beta = 0$. The relativistic effects retard the phase advance of the particles as the momentum P_n/mv_0 increases which breaks the periodicity required for the long-time limit accelerator modes.

For $N = kv_0 t_n/2\pi = 10^4$ time steps and $K = 1.3$ the standard map has particles out to $4mv_0$ where as with $\beta = 10^{-2}$ they reach only $2mv_0$ and at $\beta = 10^{-1}$ are confined below mv_0.

For $\beta = \omega/kc > 1$ qualitatively new features arise with chains of islands all nested below $2mv_0$. At $\beta = 2$ we see period-6 to period-20 island chains. The large ω/kc wave chain does not produce the stochastic heating and acceleration that is well known to occur at small ω/kc.

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Plasmas with a Single Sign of Charge
(A Review of Recent Theory and Experiment)

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Recent experiments have involved the magnetic confinement of pure electron plasmas, pure ion plasmas of one or more species, positron plasmas, and mixed anti-proton and electron plasmas. All of these are examples of plasmas with a single sign of charge. In principle, such plasmas can be confined forever and can come to a state of thermal equilibrium that is stable and quiescent. In practice, states very near thermal equilibrium are realized and confinement times in the range of a day are routinely obtained. Pure ion plasmas have been cooled to a few mK° where strong correlation effects such as liquid and crystal states are predicted theoretically and observed experimentally. Cryogenic pure electron plasmas make accessible the parameter regime of strong magnetization where a many electron adiabatic invariant constrains the collisional dynamics and the observed equipartition rate (between $T_{\parallel}$ and $T_{\perp}$) drops orders of magnitude. A class of experiments with pure electron plasmas involves largely 2-D guiding center drift dynamics and closely models the 2-D inviscid flow of an ordinary fluid. These experiments graphically illustrate a wide range of vortex dynamics. Recent theoretical analysis of the thermal equilibrium states for a 2-D guiding center model predict the possibility of equilibrium states that do not reflect the cylindrical symmetry of the confinement apparatus. These off-axis states occur for negative temperature and are closely related to $l = 1$ diocotron modes. The states may result from sufficiently violent 2-D guiding center turbulence (diocotron wave turbulence).

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Ballooning Modes in Plasmas and in Classical Fluids*

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We present a theory of ballooning modes based on geometric optics, where the modes are described as wave packets localized about their rays. In the case of plasmas, the ray is the magnetic field line, the mode is described in physical space and not in "ballooning representation" space (which is an unnecessary complication), and the ballooning phenomenon allows for solutions with complicated dependence on time (non-$e^{i\omega t}$-like) if the plasma rotates.[1]

Ballooning modes also exist in classical fluids and may be responsible for the destruction of vortex rings and tori. They possess a number of interesting features not present in the plasma case. The ray is now a streamline, but the polarization of the wave satisfies $\mathbf{k} \cdot \mathbf{u} = c$, c is any constant, and not $\mathbf{k} \cdot \mathbf{u} = 0$ (where $\mathbf{u}$ is the velocity), which would have been analogous to the plasma case with $\mathbf{k} \cdot \mathbf{B} = 0$. Thus, the family of possible ballooning modes is larger in fluids than in plasmas. We have analyzed the stability condition for all possible c. For all c except for a particular value c_0, the mode may grow at most algebraically in time, and we obtain a necessary and sufficient condition for its stability. If $c = c_0$, the mode may grow exponentially and we can give various sufficient conditions for its stability or instability. These results are a significant expansion of some recent results by Bayly.[2]

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THE ANNUAL CONTROLLED FUSION THEORY CONFERENCE

THE INTERNATIONAL SHERWOOD THEORY MEETING

A Unified Physical Scaling Law for Tokamak Energy Confinement

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From the equations which describe local transport in a turbulent plasma the scaling of the local diffusivity with the plasma parameters may be established. By appropriate choices of time and length scales for the turbulence it is shown that the scaling of the global energy confinement can be cast in two limiting forms: a short and a long wavelength scaling. The scaling laws consist of a leading term and a function F whose arguments are the dimensionless normalised plasma collisionality and beta. The scaling of the leading term in the short wavelength expression for global confinement is shown to fit both JET L and H-mode confinement data. The function F which describes the precise physical mechanism of the turbulence is bound to increase with collisionality but its dependence on the plasma beta remains uncertain. Several theoretical models are found to be a reasonable fit to the JET confinement data, however others such as DTEM can be discarded. The short wavelength confinement scaling is shown to unify a multiplicity of existing theoretical -empirical scaling laws by suitable choices of the function F. These scaling laws all exhibit a similar dependence of F upon collisionality but have different dependencies upon the plasma β. It is shown that for the JET data it is very difficult to determine the β dependence and this explains why so many apparently different scaling laws produce reasonable fits to the data. Using the leading term of the scaling, the fusion product can be extrapolated to reactor conditions (ITER) with an uncertainty factor of 4. This uncertainty can be reduced to ± 30% by the use of a similarity technique in which F is determined directly from the JET data.

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Tokamak to Tokamak Variation and Colinearity in Scaling Laws*

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The large multiplicity of scaling laws which almost fit the data is associated with the near degeneracy of the data covariance matrix. Ridge regression is applied to downweight the estimated dependencies in the poorly determined scaling directions. For the Kaye Low mode database, the most poorly determined direction is simultaneously increasing aspect ratio and elongation.

The traditional analysis assumes that only discharge to discharge variations are important. However the variation in scaling coefficients of different tokamaks is much larger than the estimated uncertainty in the scaling. We model these differences using Swamy's random coefficient model, where the tokamak to tokamak variations are assumed to be due to many small factors.

To estimate the accuracy of the estimated τ_E, we apply resampling techniques: we calculate τ_E repeatedly, each time without one of the tokamaks in the database and determine the empirical deviation in the predicted value.

*Experimental analysis in collaboration with S. Kaye. This work supported by U.S. Department of Energy, Grant No. DE-FG02-86ER53223.

A Review of Massively Parallel Computing in the MFE Program*

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Over the past several years there has been a movement towards multiprocessor computing. Traditional present-day supercomputers such as the Cray-2 have a shared memory and a limited number of very high performance vector processors. It has been recognized, however, that a more cost-effective approach might be to link together very large numbers of processors of more modest capability, each with its own local memory. These massively parallel devices, examples of which are the TMC Connection Machine II, the Intel iPSC/RX and the BBN TC2000, have recently made tremendous inroads. Although these computers are not yet general purpose, they have begun to enter the production environment, and a significant fraction of the computing community believe that the future of supercomputing lies with the massively parallel approach.

This presentation will provide an overview of massively parallel computing and will discuss both existing massively parallel efforts within the Magnetic Fusion Energy program and areas of fusion computing likely to gain from the massively parallel approach. Facilities potentially available to MFE users will be covered.

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A Banana-Passing Fluid Model for Tokamak Density Profiles

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In the low collisionality banana regime, the response of the passing and banana particles to toroidal forces is essentially distinct: passing particles accelerate whereas trapped particles drift radially. In order to model the particle transport in a physically intuitive manner, we have formulated a four fluid model for a simple electron-ion plasma involving separate momentum equations for each of the passing and banana species. The four fluids undergo collisional friction with each other and with neutrals; a radial electric field arises with the inclusion of particle sources and the collisions with neutrals. Radial plasma transport, which conserves canonical angular momentum, is modeled by scattering the configurational component of banana momentum into translational momentum of the passing particles at a rate related to the density and temperature gradients by standard neoclassical theory. It is shown explicitly that in the steady state the form of Ohm's Law is classical Spitzer, the trapped particle correction being precisely compensated by the bootstrap current. With plasma sources the effective Ohm's Law becomes $j = \sigma_{\mathrm{Spitzer}}(E + UB_{\mathrm{p}}/c)$, where U is the plasma radial flow velocity. For given radial temperature profile, we obtain a first order differential equation for the density. This profile is numerically integrated to obtain the radial density profile. The volume average density is close to the empirical Murakami/Greenwald [1] density limit $\bar{n} \propto \bar{j}$; this implies that near the density limit plasma particle confinement may be neoclassical.

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Caviton Correlations in Strong Langmuir Turbulence

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Using *incoherent scatter radar* (ISR) diagnostics, clear evidence that strong turbulence effects dominate the early-time response of the ionosphere to high-frequency heating has been obtained recently by Cheung and his co-workers (a). Power spectra obtained from the ISR data bear a striking resemblance to spectra obtained in numerical simulations of Zakharov's model of strong Langmuir turbulence (b). The 'atom' of turbulence in this model is the collapsing caviton. Through a careful study-in-comparison of these power spectra, we have come to the following conclusions (c). 1.) The turbulence is sustained by the *nucleation* of trapped (i.e., bound-state) electric fields in density fluctuations largely generated by the *collapse* and *burnout* of such trapped fields. (Linear instabilities may play a role in igniting the turbulence starting from unusually quiet initial conditions but do not sustain the observed turbulence.) 2.) Spikes in the spectra may be due to patches of temporally correlated collapsing cavitons in the strong-turbulence regime. In two-dimensional numerical simulations, we have produced ensembles of periodically collapsing cavitons that gravitate to regular lattice sites under the imposition of periodic boundary conditions. Once the lattice is established, collapse alternates periodically from site to site, and power spectra contain pronounced spikes. If indeed cavitons tend to clump into correlated patches in the heating experiments, then ISR spectra ought to demonstrate Bragg-like resonances as a function of the radar's wave vector. These resonances may have been identified erroneously with linear phenomena heretofore (c, and references therein).

I will review briefly the nucleation scenario for sustaining turbulence in the context of the Zakharov theory and the interpretation of power spectra in terms of single-caviton dynamics and caviton-caviton correlations. It is anticipated that the method of analysis presented here will find application to diagnosing the role played by localized fields in turbulent fusion plasmas.

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(b) D.F.DuBois, H.A.Rose and D.Russell, "Power spectra of fluctuations in strong Langmuir turbulence", PRL 61 p.2209 (1988).

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SHERWOOD THEORY MEETING 1990

Stability of the Gas Dynamic Trap*

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The Gas Dynamic Trap (GDT) is a novel simple mirror machine experiment developed at the Institute of Nuclear Physics in Novosibirsk in an attempt to develop a practical fusion neutron source. This device has a large mirror ratio, R, typically $R > 50$, and is designed to minimize the unfavorable curvature in the containment regime. The mechanism proposed for stabilization is due to the momentum flux gradient arising from outflow of ions from the machine. The GDT is designed to have a mean free path $\lambda_{\text{mfp}} < RL_c$ where L_c is the length of the device, thereby allowing ions to fill the loss cone, and thus provide a significant momentum flux of escaping ions in the exhaust region where the magnetic fields flares rapidly to provide good field line curvature. Past analyses showed that GDT is MHD stable if the local parallel current density is constrained to vanish at the endwall. The present work reinvestigates the MHD stability assuming the endwalls are metallic conductors, and that local parallel currents are free to flow in the walls, as long as the total current is zero. The mode is assumed to be an electrostatic flute nearly everywhere, except for a Debye sheath at the endwalls, where the mode can change rapidly but without exerting magnetic bending energy. It is shown that for this case, the stabilization effect of the ion momentum exhaust does not arise. The only stabilization comes from electrostatically trapped electrons whose momentum flux (pressure) gradient is considerably less than that of the ions.

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Fluid/Kinetic Hybrid Moment Description of Plasmas Via A Chapman-Enskog-Like Approach*

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A Chapman-Enskog-like procedure is used to develop a combined fluid and kinetic description of magnetically confined plasmas. An Ansatz of a heat flow distorted distribution function not far from a flow-shifted local Maxwellian and fluid moment equations for **n**, **T**, **V**, **q** are used to recast the Fokker-Planck equation into an equation for F -- the departure of the distribution function from its lowest order fluid moments. This approach is both systematic and natural since closure of the moment equations such as in resistive/neoclassical MHD and the Braginskii equations requires a knowledge of the distribution function, and the kinetic equations must take account of the density, temperature, momentum and heat flow conservation equations. The closure relations are provided by calculating the viscous stress tensor Π, and heat viscous stress tensor Θ from solutions of the kinetic equation for F.

The recast Fokker-Planck kinetic equation for F has been developed as follows. First, large flow velocities ($|V| \sim v_T$) are allowed for throughout the dynamics while an approximation ($|V_\alpha - V_\beta| << v_T$) is used to simplify the Coulomb collision operator. Both the test particle and field particle (or momentum, energy restoring[1]) parts of the Coulomb collision operator are retained and shown to cancel various frictional force and dissipation terms in appropriate limits. A drift-kinetic limit of the dynamics and of the collisional effects is developed and shown to reproduce and extend previous derivations.[2]

For many cases of interest (particularly when $k_\perp \rho << 1$), the dominant stress tensor components $\Pi_\parallel$ and $\Theta_\parallel$ are sufficient. (Also, the perpendicular stress tensors $\Pi_{\wedge,\perp}$ and $\Theta_{\wedge,\perp}$ can usually be calculated from the fluid theory.) Therefore, usually one needs only a knowledge of the gyrophase averaged distribution function. A particular drift kinetic equation is derived from the recast Fokker-Planck equation which is suitable for both steady state ($\omega << \nu$) and microinstability ($\omega \gtrsim \nu$) studies. The low frequency limit ($\omega << \nu$) of this equation provides a direct, deductive procedure for determining the neoclassical viscosity coefficients that are usually deduced indirectly.[3] This direct procedure will be discused. Also, extensions of the procedure to determine dynamic ($\omega \sim \nu$, $\omega << \nu$) viscosity coefficients for the neoclassical MHD equations and microinstability studies will be discused.

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Trapped Particle Effects on Resistive Ballooning Modes*

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Resistive ballooning modes with trapped-particle effects are studied in the long mean free path regime ($\lambda >> R_0 q$) using a phenomenological description of the relevant fluid equations. In this work, trapped particles are treated as separate species of particles and hence the parallel dynamics of trapped particles are governed by kinetic equations that are averaged over the length of the bounce motion. Thus, a reduced set of fluidlike equations is proposed. They incorporate effects of trapped particles and neoclassical terms (bootstrap current, enhanced ion polarization current, etc.) in addition to the usual curvature and polarization drift effects in resistive ballooning mode theory.[1] The linear coupling of the dissipative trapped particle modes with the resistive ballooning mode is considered. It is shown that the treatment adequately retains the salient features of both the trapped-particle modes[2] and neoclassical (kinetic) modifications of resistive interchange/ballooning modes.[3,4] Including the dissipative trapped-particle mode modifications, the properties of resistive ballooning modes are still described by two length scales -- namely, the connection length and the resistive scale length. Thus, adopting multiple length scale expansion techniques and solving the eigenvalue equation in ballooning space, a generalized dispersion relation with neoclassical and trapped particle effects is derived. It is shown that the electrostatic trapped particle modes (namely, the dissipative trapped ion (electron) modes) can be decoupled from the resistive ballooning mode. Finally, it is demonstrated that the resistive ballooning mode properties are significantly modified by the linear coupling to dissipative trapped particle modes and the stability properties are examined in various frequency regimes.

*Research supported by U.S. DOE grant No. DE-FG02-86ER53218 and U.S. DOE grant No. DE-FG02-88ER53264.

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On the Possibility of Deriving Trapped Particle Modes from Fluidlike Equations*

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Recently, we have developed[1] a Chapman-Enskog-like procedure for systematically and rigorously including kinetic effects in fluid moment descriptions of a magnetized plasma. The procedure basically involves determining a kinetic equation for the distortions of the distribution function away from the lowest order Maxwellian distribution function whose fluid moments are governed by conservation equations for n(x,t), V(x,t) and T(x,t). Also, we have proposed[2] (from phenomenological considerations) a set of fluidlike equations that can describe both resistive ballooning and trapped particle modes. In this work we discuss the difficulties and prospects for rigorously deriving closure relations (basically $\mathbf{B} \cdot \nabla \cdot \pi$) that describe the kinetic trapped particle effects to a sufficient degree that the resulting "fluidlike" equations can exhibit both trapped particle and resistive ballooning modes.

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1 J.P. Wang, J.D. Callen and Z. Chang, "Fluid/Kinetic Hybrid Moment Description of Plasmas Via a Chapman-Enskog-Like Approach" (paper at this conference).

2 A.K. Sundaram and J.D. Callen, "Trapped Particle Effects on Resistive Ballooning Modes" (paper at this conference).

Use Of A Fluid/Kinetic Hybrid Model For Including Kinetic And Collisional Effects In Fluidlike Models*

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Fluidlike (e.g., MHD and resistive/neoclassical MHD) approaches have been well developed for plasma linear and nonlinear dynamics studies. However, the usual fluid approaches (e.g., those based on the Braginskii equations) do not treat a number of important kinetic effects properly (e.g., Landau resonance, magnetic particle trapping, magnetic pumping, etc.). The kinetic effects can come into the fluid description through the closure relations (e.g., for π and q). We use the recently developed[1] Chapman-Enskog-like kinetic equation to determine the kinetic distortions of the distribution function and thus provide the needed closure relations, thereby yielding the fluid/kinetic hybrid equations. With this set of equations, the plasma dynamics can be studied in a fluidlike framework in which the kinetic effects are included. Expressions for the closure relations in collisionless and weakly collisional plasmas for sheared slab and tokamak geometries will be presented. Possible applications to electron drift wave instabilities and η_i modes will be discussed.

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Transport Bifurcation Induced by the Poloidal Electric Field in the Scrape-off Layer

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A model of the energy and particle transport in the scrape-off layer of a diverted plasma will be presented. The model includes collisional $\bar{E} \times \bar{B}$ particle drifts, and *ad hoc* radial diffusion. Transport along the magnetic field is classical. It will be shown that the $\bar{E} \times \bar{B}$ drift makes an important contribution to the particle flux across the separatrix into the scrape-off layer. The radial component of this flux is due to the poloidal electric field, which is generated by poloidal temperature gradients through the thermoelectric effect. This particle flux can cause a bifurcation in the steady state transport, causing the radial gradients of temperature and density to jump to a larger value at a critical power flux. The existence of a bifurcation depends on the recycling behavior at the divertor plates, which determines the net $\bar{E} \times \bar{B}$ flux across the separatrix through the boundary conditions. A comparison of this bifurcation with the phenomenology of the L/H transition will be made.

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Fluctuation-Dissipation Theorem of a Nonthermal Magnetized Plasma and Its Application to Scattering of Electromagnetic Waves

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Fluctuations in plasmas are of great interest for transport and diagnostic purposes. One way of calculating the fluctuations is the use of fluctuation-dissipation theorem [1,2]. This theorem is well-developed for thermal plasmas, while for nonthermal plasmas, the development is less complete. Since nonthermal plasmas are quite common in fusion devices, generalizations of this theorem to such cases are of interest. In this work, such a generalization is presented. The density and current correlations are calculated for a magnetized plasma. The scattering of electromagnetic waves can be calculated from these correlation functions. Recently, there is much interest in this topic for the purpose of α-diagnostics [3,4]. Interesting enhancements of scattering cross-section were found for fluctuations in the lower hybrid range of frequencies. Here, this problem is reconsidered using the extended theorem. Special attention is given to gyroharmonic resonances. Differences from previous work will be discussed.

This is a report of work sponsored by the U.S. Department of Energy under Contract No. DE-AC03-89ER53277.

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Ballooning Modes in Tokamaks with Sheared Flow*

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Sheared flows are generally believed to be strongly stabilizing and have been proposed as a means of accessing the region of second stability in Tokamaks. We have studied the stability of pressure-driven modes in the presence of sonic toroidal flows with shear small compared to the sound speed, $dV/dq << c_s$. This corresponds to the actual situation in the body of present day tokamaks. For larger flow-shear, coupling to the sound wave is strong and the magnetohydrodynamic model is no longer adequate.

As a result of the non-self-adjoint nature of the equations, the analog of the Mercier criterion is only a sufficient condition for stability against localized modes, a rather weak criterion which is of little practical use. On the other hand, the conventional ballooning representation is invalid in the presence of sheared flows[1,2] because the differential rotation destroys the lowest-order translational symmetry between rational surfaces. Nevertheless, by including the Doppler shift in the eikonal, a generalized ballooning equation can be obtained which is a partial differential equation in the extended field line coordinate and time[3]. Its solution can be interpreted as a superposition of exponentially growing lowest-order solutions of the mode equations centered on successive rational surfaces. We have solved this generalized ballooning equation analytically for a large aspect-ratio, circular cross-section plasma. The resulting stability criterion shows that although flow shear significantly reduces the growth rates, it does not completely stabilize strongly unstable modes.

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FIELD ERROR CORRECTION STUDIES FOR A REVERSED-FIELD PINCH STABILIZING SHELL*

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The departures from an axisymmetric torodial stabilizing shell and liner of a reversed-field pinch (RFP) give rise to corresponding field errors. These errors, in turn, cause island formation and field line intersections at the liner. If not kept within allowable limits, the islands and intersections can have detrimental effects on the RFP confinement fields. This is particularly important since MHD simulations and plasma measurements indicate that the RFP confinement (i.e., pressure gradient) occurs primarily in an outer annulus of the discharge cross-section. We report here studies that have been made pertaining to the poloidal gap in the shell.

Of special interest is the determination of the magnetic field deviations from an idealized compensated passive gap in a cylinder.[1] In particular we investigate the field corrections arising from (1) toroidicity, (2) finite gap width, (3) tolerances on dimensions, and (4) deviations due to structural design requirements, for the parameters of ZTH, the next generation Los Alamos RFP experiment.

For low frequency analysis (shell thickness less than skin depth) we use a magnetic field diffusion code[2] which models a thin shell with a fine mesh of loop currents whose time response to an applied field is computed from circuit theory. The circuit theory approach to eddy current calculations has also been used by others.[3,4] Comparisons of the compensated gap to the simple overlapped and butt gaps are made. We have extended the idealized cylindrical results and obtained a 2-D partial differential equation describing the toroidal and poloidal shell thickness variations to give a toroidally symmetric response to an applied vertical field. For special trajectories on the shell surface, these toroidal and poloidal variations can be obtained by solving first order ordinary differential equations.

For the higher frequency domain where the thin shell approximation is not valid, we utilize two and three dimensional finite element field diffusion codes.[5]

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EFFECT OF SHEARED TOROIDAL PLASMA FLOWS ON THE EQUILIBRIUM AND STABILITY OF TOKAMAKS

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Several present day tokamak experiments have reported large toroidal plasma rotations induced by neutral beam injection during auxiliary heating. The measured rotation profiles [1] indicate that velocity shear can be significant. We examine the effect of such sheared flows on the equilibrium and stability of tokamak plasmas. Using the generalised MHD equilibrium equations for axisymmetric rotation [2], we carry out a detailed numerical investigation of the form of magnetic surfaces and other equilibrium quantities as a function of the velocity shear parameter. In certain simple limits, approximate analytic expressions are also obtained for the ellipticity near the magnetic axis, the shift of the magnetic axis and the anisotropy in pressure induced by the velocity shear. Next, the influence of these equilibrium modifications on ideal ballooning modes is studied using a modified WKB prescription. Shear is found to have a significant stabilising influence on them and might prove useful for creating a stable path to the second stability regime.

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Gyrokinetic Simulations in the Presence of Collisions*

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An electron-ion binary collision model[1] using the Monte Carlo method is applied to gyrokinetic simulations of plasmas. The model conserves both momentum and energy. Its various numerical aspects are presented and discussed. Thermal relaxation processes such as slowing-down and velocity diffusion of test particles are studied, and the results are in good agreement with theory. As the first application of the model in gyrokinetic simulations, we study nonlinear evolution of drift instabilities[2] and anomalous diffusion in the presence of collisions. The weakly collisional regime is considered($\nu_{ei}/\omega_{*e}<1$). Comparisons are made with the results obtained by using the Lorentz model where momentum is not conserved. We observe some quantitative difference in the particle flux in drift wave instabilities in a shearless slab model during the post-saturation phase of the instability. The second application is concerned with gyrokinetic simulation of neoclassical diffusion in a model toroidal magnetic field.[3] Without self- consistent field and including the grad-B and curvature drifts as well as magnetic mirroring, the collision model is able to recover some of the basic features predicted by neoclassical theory (within 20%) with regards to scaling of diffusion coefficients. Modification of this diffusion due to imposed radial electric fields will also be presented.

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The statistical dynamics of turbulent plasma convection*

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Consider transport due to steady-state turbulence. Let ψ be a vector of macroscopic variables—*e.g.*, $\psi = (n, T)$. Then a general representation of the vector of radial fluxes $\boldsymbol{\Gamma}$ is $\boldsymbol{\Gamma} = -\mathsf{D}\cdot\partial_r\langle\psi\rangle + \boldsymbol{\Gamma}_U$, where the diffusion tensor D is allowed to depend on $\partial_r\langle\psi\rangle$ and $\boldsymbol{\Gamma}_U$ is assumed to depend more weakly on $\partial_r\langle\psi\rangle$ than the diffusive term. The projection onto one component, say n, is $\Gamma_n = -D_{nn}\partial_r\langle n\rangle + G_{Un}$, where $G_{Un} \doteq \Gamma_{Un} - D_{nT}\partial_r\langle T\rangle$. Experimentally, the presence of "convective" terms G seems indicated by analysis of the data, but their origins are relatively poorly understood. It is reasonable to assume that both D and $\boldsymbol{\Gamma}_U$ are due to microturbulence. One popular and plausible scenario is that $\boldsymbol{\Gamma}_U$ vanishes, so that terms such as G_{Un} just describe off-diagonal turbulent diffusion. The other limiting possibility is that the cross-diffusion terms are unimportant, so that, *e.g.*, $G_{Un} \approx \Gamma_{Un}$. It has been suggested that a nonvanishing $\boldsymbol{\Gamma}_U$ describes a *frictional* effect arising only because of the self-consistency of the turbulence, analogous to the polarization drag in classical kinetic theory. This latter idea is examined in detail for a general scalar model in which no cross-diffusion terms can arise. A new and novel calculation of the Fokker-Planck diffusion coefficient $D \doteq \langle\Delta x^2\rangle/2\Delta t$ is performed, using no ingredients other than ordinary perturbation theory. It is crucial to evaluate $\langle\Delta x^2\rangle$ through *fourth* order in the fluctuations. Although the conventional "renormalized quasilinear" diffusion coefficient $D_{\rm rq}$ emerges as one term in the calculation, other "noise" terms arise as well that are manifestly of the same order as $D_{\rm rq}$, so that $D \not\approx D_{\rm rq}$. Although these terms are somewhat reminiscent of classical polarization drag, they arise not from the first Fokker-Planck coefficient but from the second; they are diffusive, not frictional, and contribute to the diffusion tensor, not to a convective term Γ_U. The difference between D and $D_{\rm rq}$—*i.e.*, the physical significance of the noise terms—can be understood by noting that the true diffusion coefficient D must be computed by integrating along the actual (random) trajectories of the particles or fluid elements. In the presence of turbulence, those trajectories are correlated in subtle, although well-defined and calculable, ways to the turbulent fluctuations. Many of those correlations are arbitrarily neglected in deriving $D_{\rm rq}$. By exhaustively cataloging the actual statistical correlations, one is led to new, physically intuitive interpretations of the noise terms. In fact, these terms are not new. They can be mapped uniquely onto formally exact expressions for the flux that follow from the general statistical dynamical theory of turbulence; however, the detailed relation of these formulas, either exact or in the direct-interaction approximation, to the Fokker-Planck theory has been heretofore lacking. Some of the noise terms form the starting point for the so-called clump theories of turbulence. However, for the computation of transport coefficients no appeal to the clump interpretation need (or should) be made; the dominant effect of the noise is grossly different than that assumed by the clump algorithm. All these ideas can be illustrated by considering the statistical dynamics of Hasegawa–Mima-like equations. For this representative case, the decomposition of the flux into "diffusive" and "convective" parts is shown to be unnatural. Neither part by itself provides an accurate description of the density transport; cancellations of order unity occur between them so that their sum reduces to the usual result proportional to the growth rate times the spectral intensity. In summary, the existence of frictional terms $\boldsymbol{\Gamma}_U$ is not supported by theory. The ideas described here unify a variety of seemingly unrelated calculations in the literature, provide new physical understanding of complicated nonlinear terms, and demonstrate the inappropriateness of a number of popular assumptions. They also suggest specific calculational methodologies, such as the development and utilization of realizable statistical approximations based on Langevin representations of the noise.[1]

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Localized source effects on neoclassical transport and L-H transitions.

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The plasma particle source present in the edge of tokamak plasmas can modify neoclassical flows and fluxes, including the self-consistent value of the electric field. Its effects on neoclassical transport in plateau regime are studied in a kinetic approach. The resulting modifications to particle flux and electric fields are correlated with the L-H transition characteristics. The effects are proportional to the intensity of the source, and hence more important when the X-point is close to the walls. It is shown, under reasonable assumptions, that when the ion grad B drift points towards a localized particle source the inward electric field is increased. This could help stabilize fluctuations and reduce anomalous transport. A bifurcation mechanism based on electric field value could make a small perturbation due to the particle source very important in marginally different states.

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Minimum Energy Dissipation States and Predictions of the MHD Configurations in Fusion Confinement Devices

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An assumption of minimum energy dissipation rate has been used to predict, analytically, MHD configurations for electrically-driven, periodic cylinders of magnetofluid.[1] We explore the implications of this assumption by minimizing the MHD energy dissipation integral, subject to constraints. The most troublesome of these constraints is the pointwise MHD Ohm's law, which is a relation between the velocity and the magnetic field (and its curl). An expansion method, involving Chandrasekhar-Kendall functions as an orthonormal basis, has been developed.[2] For relatively weak driving (low pinch ratio and Reynolds-like numbers), the expansion can be truncated at low order, and states obtained which agree qualitatively with some MHD solutions obtained numerically. The boundary conditions are different, however, and there are quantitative discrepancies. The problem is being pursued further.

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Statistical Modeling of Drift Wave Turbulence*

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We are undertaking a study of plasma drift wave turbulence using a combination of methods—numerical simulation, closure approximations, and analytic predictions. We give results for the equilibrium statistical mechanics of a two-field drift wave model. Using a numerical simulation code, we are able to consider the process of relaxation to equilibrium. We verify analytic estimates of spectra and quantify predictions of relaxation rates. We are able to demonstrate the importance of the cross-correlation spectrum and show how its presence retards the relaxation of the density spectrum. This cross-correlation quantity is often neglected in turbulence model calculations in both fluid dynamics and plasma physics. We discuss the use of statistical turbulence models of the Markovian (EDQNM) and Direct Interaction (DIA) types which retain the cross-correlation evolution equations. Preliminary results from a DIA code are given and compared with the direct simulation results. We note that EDQNM models, which are more ad hoc than DIA, have some restrictions based on our simulation results.

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Singular and Nonsingular Plasma Equations for the Collisionless Sheath*

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In the kinetic treatment of the one-dimensional collisionless plasma sheath, the plasma region is approximated by an integral equation which is often called a plasma equation. This equation can be singular or nonsingular depending on the source term. It is shown that in the singular case, a physically reasonable solution can be obtained only when the Bōhm criterion is imposed as a boundary condition. While for the nonsingular case, a solution can exist only for some special edge potential at the sheath edge, this potential guarantees that the Bōhm criterion is satisfied.

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SYMMETRIES AND GLOBAL TRANSPORT EQUATIONS(•)

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The anomalous transport of the electron thermal energy and that of the longitudinal current density are related to each other and described by an appropriate "diffusion" matrix equation. The symmetry properties of the matrix diffusion coefficients are identified and used to prescribe realistic conditions [1] on the radial profiles of the electron temperature T_e, and of the current density $J_{\|}$, while minimizing the relevant entropy production.

Referring to a high temperature toroidal plasma configuration, we adopt the condition that the global momentum transfer from the electrons to the ions, over the entire plasma column, is that given by the neoclassical collisional resistivity [2]. However the thermal-viscous diffusion term introduced in the relevant "Ohm's law" redistributes the electron-ion momentum transfer in such a way as to produce well-behaved ("canonical") current density profiles that are consistent with equally well-behaved temperature profiles. By contrast, neoclassical resistivity alone produces [3] "strange" current density profiles characterized by a cusp at the center of the plasma column.

The matrix symmetries require a new term in the electron thermal energy balance, in addition to the thermal conductivity, that corresponds to the thermal-viscous term in "Ohm's law". This term has a component due to the current density gradient with a sign opposite to that of the temperature gradient. We argue that in experiments where only ohmic heating is present, a condition of minimal transport determines, given the total plasma current, the point of operation in $(T, J_{\|})$ phase space. Injected heating breaks the symmetries, as the role of the electric field is reduced simply to that of driving the current that confines the plasma. Thus a degradation parameter is introduced to describe the transition to injected heating regimes where a form of the thermal conductivity inferred from the properties of known microinstabilities is adopted [4].

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The Neoclassical Transport of Toroidal Momentum in Tokamaks*

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It was shown recently[1] that the low energy ions produced at the edge of the plasma by recycling or gas puffing, due to the combined effects of a large collision frequency for pitch angle scattering (with impurities present) and electrostatic diffusion, diffuse inward too rapidly to thermalize with the outward diffusing energetic ions and a near singularity will occur in f_{i0} at low energies. The presence of a moderate concentration of such excess low energy ions ($\sim 10\%$) was necessary to explain the density asymmetry measurements in PDX, where conventional theory fails to explain even simple momentum balance within a magnetic surface. The presence of these excess low energy ions leads to simple neoclassical explanations for many hydrogen and impurity ion transport phenomena. The most dramatic change is in the neoclassical prediction for toroidal momentum transport. If for convenience a Maxwellian distribution is assumed for the excess low energy ions (n_c, T_c) and their temperature satisfies $m_z/m_i \gg T_i/T_c \gg 1$, the diagonal term in the transport matrix proportional to the gradient of the toroidal velocity (V_T) for $|V_T| \ll v_{Tz}$ is given by

$$\pi_{\phi r} = -3.3 n_c (r/R)^2 \nu_{cz}\, \rho_{z\theta}^2\, m_i\, V_T' \,. \tag{1}$$

This is typically 10^2 larger than the previous neoclassical value for a pure hydrogen plasma and gives the required increase for order of magnitude agreement with experiment. Allowing for large V_T and other contributions one finds the extra terms to be added to Eq. (1)

$$\begin{aligned} \pi_{\phi r} = -n_c (r/R)^2 \nu_{cz}\, \rho_{z\theta}^2\, m_i \Bigg\{ & \left(\frac{m_z V_T^2 - \frac{R}{r} Ze\, \tilde{\Phi}_0}{T_z} \right) V_T' + 2 V_T \left(\frac{p_z'}{p_z} \right) \\ & - \Omega_{z\theta} \left[\frac{m_z V_T^2 - \frac{R}{r} Ze\, \tilde{\Phi}_0}{T_z} + \frac{R \tilde{n}_c}{r\, n_c} \right] \Bigg\} , \end{aligned} \tag{2}$$

where $\tilde{\Phi}_0$, $\tilde{n}_c$ are the $\cos\theta$ parts of the potential and n_c. The first two terms will enhance the momentum diffusivity since they transport outwards momentum with the sign of V_T. The terms in the square brackets transport positive momentum outwards and could explain both the improved momentum containment with counter NB injections[2] and the fact that once substantial counter rotation has been established it can be maintained with fewer beam lines and more gas puffing.[2]

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Resistive Stability at High-β*

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While there is a great deal of theoretical effort exploring the path to the "second stable" regime of ideal ballooning modes in tokamaks, both small and large tokamaks operating today are largely confined to the first stable regime, where β is limited by the Troyan-Sykes limit $\beta_c = c(I/aB)$. We have started a systematic, self-consistent, study of this operational limit on β using our toroidal, full MHD code *CTD*. Starting in a low-β state where finite-β effects are unimportant, the nonlinear evolution of the plasma column is observed under the combined effects of ohmic and auxiliary heating, and parallel and perpendicular transport. As β increases, the plasma continuously evolves through a series of neighboring equilibria with "physical profiles" consistent with the transport coefficients used. As it was found earlier[1], in strongly sawtoothing discharges at high-β, each sawtooth crash that raises q_o to unity leads to moderate-m MHD activity outside the inversion radius that tends to generate localized stochastic layers. During this period, modes resonant immediately outside the mixing radius, such as $m/n = 5/4$, are commonly observed and may provide an alternative explanation to some experimental observations. As β increases further, large stochastic layers develop; however, "the computational operational limit" occurs usually in the form of an $n = 1$ mode with a strong ballooning character.

The resistive stability of the second stable regime is also being investigated. Although the Δ'-driven branch of the resistive ballooning modes is predicted to be stable in this regime[2], there exists an electromagnetic branch, with an energy source within the resistive layer, that is expected to be unstable[3]. We believe we have identified this mode in the first stable regime and are trying to isolate it in the second stable regime. Even below the Troyan limit, these modes can have a significant effect on confinement; in particular, they may play a role in incomplete sawtooth crashes that do not fully reconnect.

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Influence of Radial Electric Fields on Turbulent Fluctuations in Toroidal Plasma

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Although the influence of a radial electric field on particle and energy confinement was noted in early auxiliary-heated tokamak experiments, the importance of the radial electric field for tokamak confinement had not been widely recognized (nor understood) until recently, when theoretical and experimental investigations focussed on enhanced confinement regimes. In this paper, we extend our previous works [1,2] which initiated the recent interest on the effects of the radial electric field on anomalous transport, to include a crucial symmetry-breaking terms in previously studied model resistive fluid equations. The model equations are solved analytically by means of renormalized two-point theory to obtain spectral information about the saturated turbulence. The most significant results from analytical calculations is the change of the spectral fall-off rate which is dependent on the strength as well as the sign of the radial electric field. The corresponding resistive fluid equations are then solved numerically to verify the theoretical predictions and obtain more quantitative information. Indeed, the results of numerical calculations clearly show that the spectral shape changes with the magnitude and the sign of E_r. This agreement between analytical predictions and results of numerical calculations confirms that our simple model contains the most crucial physics ingredients to understand the role of E_r on plasma turbulence. We will discuss the implication of these findings on anomalous transport of toroidally confined plasma and the applicability condition of this "generic" effect of E_r on a wide range of plasma regimes.

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Observation of Temperature Dependent Transport in TFTR*

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Electron particle, and heat transport coefficients are measured during a controlled scan of plasma temperature with the electron density, plasma current, toroidal magnetic field held constant. The purpose of the experiment is to determine if there is any temperature dependence to electron transport for auxiliary heated plasmas. The particle transport is measured with a perturbative gas puffing technique where a small amount of gas is introduced during the steady state of a neutral beam heated plasma, and the time evolution of the density profile and the particle sources are used to ascertain the particle transport coefficients. The analysis uses a general flux relationship that allows for nonlinear transport, and is fitted to the experimental particle flux over the time of the perturbation at each plasma radius: $\delta\Gamma=(\partial\Gamma/\partial\nabla n)\ \delta\nabla n + (\partial\Gamma/\partial n)\ \delta n$ where the transport coefficients are in terms of these partial derivatives. The electron thermal diffusivity profile, $\chi_e(r)$, is obtained from routine equilibrium power balance analysis. The analysis of the particle transport coefficients yields local temperature dependencies on the order of T_e^{α} where α = 1.5-2.5, and the thermal transport analysis indicates that χ_e depends of T_e^{β} where β = 2.5-3. It has not yet been determined if the difference in the temperature dependence is significant.

Taking the particle transport partial derivatives $\partial\Gamma/\partial\nabla n$ and $\partial\Gamma/\partial n$ at each radius one can look for additional dependencies in the data. After normalizing out the temperature dependence in the data, there are few parameters that fit the data and comply with the cross partial constraint $\partial/\partial n(\partial\Gamma/\partial\nabla n)=\partial/\partial\nabla n(\partial\Gamma/\partial n)$. The best fit to the data is a single flux term: $\Gamma\propto(\varepsilon T_e^{1.5-2.5}/n_e L_n^2)\nabla n$, or $(\varepsilon T_e^{1.5-2.5}/n_e L_n L_{te})\nabla n$. Both are consistent with electrostatic turbulent transport from drift waves.

SPECTRAL METHODS FOR COMPRESSIBLE FLOWS

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Galerkin spectral method is extended for compressible flows.[1] Two specific probelms and their solutions are presented.

Compressible flows require computing higher order (higher than quadratic) non-linear products. Multiple set of grids are introduced to compute aliasing error-free products. This generalizes Orszag-Patterson transform technique for quadratic products.

A second problem, that of Galerkin reciprocal is introduced. Nature of the problem is discussed and some solutions are suggested. Re-writing the equations of compressible fluids and MHD in terms of specific volume is considered a reasonable solution.

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Self-consistent Plasma Effects on Magnetic Field Ripple *

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The self-consistent plasma effects on the magnetic field ripple in a tokamak is studied in a cylindrical model with finite pressure. An appropriate Grad-Shafranov-like equation is derived using a suitable flux coordinate system in which the ripple contribution to the flux is properly included. With the choice of a *'flat'* current density profile, this can be solved analytically to give a ripple-corrected Bessel function model. In this model the plasma produces a small enhancement of the externally imposed ripple field, consistent with the low beta $3D$ numerical simulations of *Johnson and Rieman.*[1]. Other effects, such as, for example, a more realistic current profile and toroidal effects could be added to the model.

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Fast Wave Current Drive Calculations Using the Geometrical Optics Code RAYS*

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The Oak Ridge National Laboratory geometrical optics code, RAYS, has been modified to study effects near the ion cyclotron frequency. The cold plasma dispersion relation is used to propagate the rays with arbitrary ion masses and species number permitted. Various wave damping models have been incorporated allowing calculation of electron Landau damping, TTMP, ion cyclotron damping, and alpha particle absorption along the ray trajectories. A simple fast wave current drive model developed by D. Ehst has also been installed in RAYS. The 2D full wave code ORION is used to model the ICRF antenna and to initialize the rays in the RAYS code to be representative of a realistic antenna. Calculations will be presented for ITER and for a proposed fast wave current drive experiment on DIIID. Comparison is made with the results of the ORION code.

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Massive Parallelization Of Fluid Turbulence Simulations In Tokamaks*

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Efforts in the area of massively parallel algorithm development have concentrated on the 3-D fluid turbulence simulation code TRB originally developed by Waltz of GA. During the past year the code was modularized under BASIS and optimized for performance on the Cray-2 to facilitate comparison and testing across architectures and algorithms.

Central to the performance issues is the scaling with problem size of the time required to evaluate the non-linear mode coupling due to EXB convection. The time required for a direct evaluation of this coupling in a single processor computer scales as the square of the number of modes, whereas the evolution of the mode amplitudes scales linearly with the number of modes. The scaling of performance on a massively parallel computer depends strongly on the suitability to the architecture of the algorithm used.

Two data parallel direct convolution algorithms suitable for CM2 implementation were developed and tested on the Cray-2 and implemented and tested on the CM2; one involves vector parallel variables and employs vector indirection, the other uses segment scans. Both algorithms rely mostly on NEWS routing.

Concurrent development of a pseudospectral technique for evaluating convolutions using Cray Research coded 2-D FFT's was completed and tested on the Cray-2. Performance on the base case (160 modes, 128 radial meshpoints) of the pseudospectral method was 20% faster than the direct method (on the Cray-2). This result bodes well for scaling to larger cases since the scaling of computer time with problem size for the pseudospectral method corresponds favorably with that of the evolution algorithm. The same technique is currently being implemented and tested on the CM2 using FFT routines developed by TMC for the CM2.

The original time evolution algorithm, based on the recursive Gauss technique, is being replaced with a parallelizable scheme on both the Cray-2 and the CM2 using (cyclic reduction and/or) SOR.

Work has begun on the design and development of a set of algorithms appropriate for implementing TRB on the MIMD BBN TC2000 using the split-join paradigm supported by PCP (Brooks) and its Fortran successor PFP.

Work has also begun on the creation of a graphics visualization post-processor for TRB using a TAAK graphics accelerator.

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Particle Simulation on the NCUBE Concurrent Multiprocessor

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Both 1D and 2D electrostatic particle simulation codes have been developed on the NCUBE in the UCLA Mathematics Department, as part of a study of techniques of converting and optimizing such programs on this type of multi-node computer.

The simulated system is divided lengthwise (along the x-direction) into overlapping sectors, each assigned to a node of the NCUBE. In 2D, the Poisson solution is based upon two 1D exponentially declining Green's functions in x, preceded and followed by 1D FFT's in the y-direction, and by form-factor convolutions in x for smoothing of the charge and force arrays. This Green's function approach has several important advantages over the conventional FFT-only algorithm: no need for strict synchronization among the nodes; greater flexibility in dynamically reallocating the electrostatic grid among the nodes (needed for load balancing); and reduction in internode communications.

The codes have been designed to avoid strict synchronization. Instead they have been logically structured as sections, each of which is executed upon receipt of the appropriate message from another node or the host. Messages are sent as early as possible within each section in order to minimize idle time between sections when no incoming messages are pending at the nodes. This has required each node to send five messages per timestep, rather than the absolute minimum of one to the host and one to each adjacent node. The gain from avoiding strict synchronization exceeds the loss from the extra message transfers.

Load balancing is accomplished by an initial allocation of particles and gridpoints to the sectors, plus a dynamic algorithm that anticipates the flux of particles across the sector boundaries and moves these boundaries in such a way that the accumulated flux of particles and appropriately weighted gridpoints is maintained close to zero.

As test cases, scaled systems of 8192 particles/node and 2048 gridpoints/node were used. Even with two oppositely moving beams, each of one half the system length and each containing one quarter of the total particles, where dynamic particle-density ratios as high as three will develop, the efficiency loss with 32 nodes versus one node has been reduced to 0.1% for both 1D and 2D, and losses as low as 0.02% have been seen in special cases. The increase of efficiency loss with number of nodes is less than logarithmic.

An NCUBE of 32 nodes of 512 kbytes each, as used in this study, allows 2D simulations as large as 256k particles and 64x1024 gridpoints, and 1D simulations as large as 512k particles and 128k gridpoints. Since NCUBE's of up to 1024 nodes are available, these would permit correspondingly larger simulations. However, the present 512-kbyte limit on memory per node would probably not permit more than a doubling of the width of the 2D system to 128 gridpoints, because of the x-direction convolutions in the current code. Therefore a conventional 2D FFT-only Poisson solution has also been implemented, in the hope that the NCUBE's asynchronous internode communication will yield significantly smaller efficiency losses than have been obtained with synchronous-communication hypercubes.

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Thermal α-particle Transport Study

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Thermal α-particle transport is a crucial issue in α-ash buildup unless buildup turns out to be less than expected or is controlled externally, ignition may be prevented in a tokamak reactor. For ARIES or ITER-like plasma, ignition is prevented with $\gtrsim$ 10% ash buildup. Due to the uncertainty on thermal α-particle transport, a 1-1/2-dimensional sensitivity study of the influence of various models for helium transport coefficients on the fusion power density in a tokamak reactor is in progress using the BALDUR code. As a test case, a plasma with major radius = 7.245m, aspect ratio = 4.5, toroidal field = 10.711T, and plasma current = 10.353MA is considered. The scrape-off loss and the particle recycling effects on the plasma boundary are included. Preliminary results, with neoclassical model, show that ash builds up from the level 2.5% to 10% within 15 seconds with the above plasma parameters. However, various transport models, such as neoclassical/turbulent theoretical models and semi-empirical/experimental correlations, are under consideration, and results for these cases will be presented. Based on this, comments about needs of experimental measurements relative to thermal α-particle transport will be provided.

Basics of Tearing Modes

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The tearing mode is reconsidered under the most simplifying assumptions, MHD valid, the initial equilibrium has two ignorable coordinates (y and z), the perturbed (torn) equilibrium has one ignorable coordinate (z) and is periodic in y with the period L, the flow is incompressible and only in the x and y directions, and conducting wall boundary conditions are imposed.

The perturbation is specified as a change of the (ideal) MHD constraints. The initial equilibrium has a singular surface where the flux function has a maximum. The perturbed equilibrium has a string of islands near the initial singular surface. The perturbation of the constraints is determined by the difference, $\Delta\psi$, between the flux function values at the elliptic and hyperbolic axes of the island string. It is found for this perturbation that ideal MHD is violated only where the current density is infinite. We conjecture that the initial equilibrium is unstable if the magnetic energy of the equilibrium of the perturbed constraints, $\mathcal{E}$, is a decreasing function of $\Delta\psi$ for small values of $\Delta\psi$.

In the special case, $L \to \infty$, it is easy to find [1] an upper limit for $\mathcal{E}(\Delta\psi)$. It is found that only initial equilibria with constant z-component of the current density are stable according to the conjecture. This result differs from the conventional [2] stability criterion.

The difference between this new and the conventional results may be that the new treatment can be considered nonlinear. Following the new prescription (but linearizing in the displacement) yields the conventional result. Also, the lower limit of the free energy, $\mathcal{E}(0) - \mathcal{E}(\Delta\psi)$, is found proportional to $\Delta\psi^{5/2}$ rather than $\Delta\psi^2$. In addition, the changes of the field associated with the upper limit for $\mathcal{E}(\Delta\psi)$ are quite different from those of the conventional theory.

Simple estimates of the effects of finite values of L suggest that the above-mentioned free energy may be negative for small values of $\Delta\psi$ but positive for larger values of $\Delta\psi$, suggesting the existence of a threshold for development of an instability. This threshold is found to be very small near the surface of a tokamak; thus, the tearing mode m·y be a driver of surface turbulence of tokamaks.

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Generalized EDQNM closure applied to a two-field fluid model of the ion temperature gradient mode.*

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The current initiative to understand turbulent transport has led to considerable interest in the η_i mode. While an accurate description of this mode may require a full kinetic treatment, some features may be accessible from a simple fluid model describing the coupling of ion pressure and electrostatic potential. One such model has been studied numerically by Ottaviani et al.[1] with a pseudo-spectral code. The objective of the present work is to apply statistical closures to this fluid model using the code `DIA`[2] and to compare the results to direct simulations. One purpose in making this comparison is that closures can yield insight into details of the nonlinear interactions, perhaps providing a better understanding of the physics underlying the saturation mechanism. This comparison also provides us with the first realistic test of a recently-proposed generalization[3] of Orszag's eddy-damped quasi-normal Markovian (EDQNM) closure. The generalization corrects two deficiencies in the original EDQNM closure.

First, the original closure was not *realizable* in the presence of non-Hermitean effects such as waves. A closure is said to be realizable if it is guaranteed to be the exact description of a real statistical problem. The EDQNM was originally developed for incompressible Navier-Stokes turbulence, which has only viscous dissipation in the linear term. While the original EDQNM is realizable for these problems, it is generally not realizable for the problems of plasma physics (and geophysics) where wave phenomena are important. The non-realizability of the original EDQNM closure is linked to the triad interaction time becoming negative. In light of the fact that the full direct-interaction approximation (DIA) is realizable even for non-Hermitean problems, an attempt to understand the failure of the original EDQNM is made using perturbation theory. The relation of the Markovian closures to the so-called quasi-stationary form of the EDQNM is also examined.

Second, the original EDQNM was developed only for one-field problems. A nontrivial matrix generalization yields a realizable closure for multiple-field problems even in the presence of arbitrary non-Hermitean coupling. This second generalization is obtained through reasoning similar to that used by Kraichnan to generalize the test-field model (TFM) to multiple fields. (However, the original TFM itself is realizable only for Hermitean dynamics. Fortunately, the analogy to the EDQNM is close enough that we can also suggest a possible extension of the TFM to non-Hermitean problems.)

In this work we use the realizable EDQNM to examine a physics-based model of the toroidicity-induced η_i instability. We expect this new, realizable Markovian closure will be a useful tool for studying more general turbulent systems as well.

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Bifurcation of Poloidal Equilibrium Flows and Transport Fluxes in Tokamak Plasmas with Impurities

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Tokamak equilibria, described by poloidal (and toroidal) flows and poloidal density and temperature variations in the flux surface, have been found [1-3] to be essential in determining the radial transport. Recently, the L-H transition has been suggested [2-4] to be caused by a bifurcation of the poloidal equilibrium flows (and the ambipolar radial electric field). Several different mechanisms can be invoked to lead to such bifurcations. Here, we focus on the nonlinearities introduced by strong main ion-impurity ion parallel friction. When $\Delta \equiv \left(\frac{\rho_{pi}}{r_n}\right) Z^2 \frac{\nu_{ii}}{\omega_{ti}} \sim 1$ (readily satisfied in the outer region of the plasma) an order ϵ poloidal variation $\tilde{n}_j(\psi, \theta)$ of the impurity density is created (rather than the usually assumed much smaller variation $\sim \epsilon(\rho_p/r_n)$.) Hence the neoclassical multispecies fluid equations become nonlinear in $\tilde{n}_j$ and ensuing ambipolar potential $\tilde{\Phi}(\psi, \theta)$ which couple into the equations determining the poloidal flows $V_{\theta j}$; $j = i, z$. Balancing the parallel viscous force $\vec{B} \cdot \nabla \cdot \overleftrightarrow{\Pi}_j$ (driven by $V_{\theta j}$) against the parallel friction $R_{\| iz}$ (which is nonlinear in $\tilde{n}_j$ and $V_{\theta j}$), naturally leads to multiple solutions for the poloidal flows and poloidal density variations. Due to the inclusion of temperature variations, the nonlinear effects are also propagating into the coupled heat balance equations. The ensuing nonlinear system of equations for the main ions and impurities is analyzed analytically and numerically. One finds three roots for the poloidal equilibrium of which two are stable. The corresponding radial transport fluxes exhibit a lower and a higher confinement solution for the tokamak plasma.

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Studies of Feedback Stabilization of Axisymmetric Modes in Deformable Tokamak Plasmas*

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It is well known that tokamak plasmas with strong cross-sectional shaping are subject to severe axisymmetric ($n = 0$) instabilities that can destroy the plasma on the ideal MHD time scale. Such modes can be partially stabilized by placing a conducting wall around the plasma, but they remain unstable on the L/R time of the surrounding conductors. This time scale is, however, much shorter than the length of the discharge in modern tokamak experiments; therefore, an active feedback system is needed to further stabilize the plasma over the time of the discharge.

The efficacy of the feedback system is highly dependent on the details of the active and passive feedback system and of the plasma itself. In the past, the stabilizing properties of these feedback systems have been analyzed using simplified models that treat the plasma as a collection of filamentary currents, or as having purely rigid motion. However, this, is often not a good representation, because plasmas with strong cross-sectional shaping can have large nonrigid components to their displacements. In fact, it has been shown[1] that plasmas with strong cross-sectional shaping can remain unstable under the effects of a feedback system that would stabilize a plasma with purely rigid motion.

We have developed a *non*-ideal MHD linear stability code, NOVA-W, that calculates the linear stability of the full nonrigid axisymmetric motion with passive and active feedback systems included. We have modified the vacuum calculation of the NOVA code[2] to include the effects of resistive conductors and feedback currents in the vacuum region. The code can calculate the growth rate and eigenfunction for the vertical instability of a tokamak plasma surrounded by arbitrarily shaped resistive conductors with or without an active feedback-system of arbitrary configuration based upon poloidal flux loop measurments. Results from the NOVA-W code will be presented for various feedback-system configurations for highly shaped plasma equilibria, including the CIT and ARIES-1 reactor designs. Emphasis will be on the deformable character of the plasma motion and its influence on the effectiveness of particular feedback system configurations. We will also examine active feedback on plasmas with poor passive stabilization (approaching ideal time scales) and the effect of discontinuous conducting walls.

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Canonical Hamiltonian Guiding Center Variables

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A simplification of the canonical Hamiltonian variables for the guiding center motion of a charged particle in a general toroidal field is obtained using the Lagrangian formalism developed primarily by Littlejohn.[1–5] It is shown that different choices of the second order parallel velocity result in different canoical variables. A particular choice results in simplified variables. Different choices of variables is shown to result in identical particle orbits, also when the magnetic field is stochastic.

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SCENARIOS OF ICRH IN PHAEDRUS-T

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The Phaedrus-T tokamak will study various aspects of ICRH physics such as wave excitation, power deposition, impurity production, effects of antenna and Faraday shield structure, antenna phasing, near antenna fields, etc. Here we present results of numerical calculations for the most important regimes where the expected antenna loading resistance is approximately 3 Ohms and the power deposition profile peaked at the plasma center. The code FASTWA gives 3-D pictures of the fast wave RF field distribution for different wave components and calculates power deposition profiles by different mechanisms for ions and electrons. Results presented for the two strap antenna used in the first ICRH experiments on Phaedrus-T show the essential changes with antenna phasing, minority concentration, density and temperature values and profiles. Calculations show that in some regimes fast wave absorption by electrons can be an essential part of total absorption so experiments on ICRF fast wave current drive can be successful.

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FRACTAL TRANSPORT IN STOCHASTIC MAGNETIC FIELDS

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Abstract - In the present report an examination is given to the non-self-consistent problem of evaluation the effective heat conductivity χ_{eff} in a specified "braided" magnetic field $\vec{B}=B_0\hat{z}+\delta\vec{B}(z,y,z,t)$, where the random perturbation $\delta\vec{B}$ parameters ($b_0\equiv\delta B_\perp/b_0\ll1$, L_0 is longitudinal, δ transverse correlation lengths) are considered as known (e.g. from an experiment). The transport properties depend crucially upon the dimensionless parameter $R=b_0L_0/\delta$. The *quasi-linear limit* $R\ll1$ has been discussed by many authors [1-3]. The opposite case $R\gg1$, corresponding to more strong magnetic perturbations, has caused much misunderstanding in the literature, and, as a matter of fact, has not been given a proper examination.

In the present report it is shown that study of this transport regime requires the use of the percolation theory methods [4], hence, the limit $R\gg1$ has been referred to as the *percolation limit*. In this case the transport pattern turns out to be rather non-trivial. In particular, the main heat flux is concentrated on fractals with the dimensionality of 7/4, consisted of a small fraction of percolating magnetic lines, i.e. lines declining from non-perturbed magnetic surfaces to distances much greater than the transverse correlation length δ.

The reason for for such a long-correlated behavior is the special geometry of magnetic lines, whose (x,y)-plane projections are nearly the isolines of a random function $\psi(x,y)$, proportional to the z-component of vector potential. Thus, fractal properties and distribution function of random function isolines over their sizes [4] should be employed, leading to the percolation theory methods. In the report numerous anomalous transport regimes are studied [5].

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TURBULENCE SATURATION AND POLOIDAL FLOW VELOCITY*

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The nonlinear evolution of resistive instabilities with ω^* effects included generates a DC radial electric field (poloidal velocity) through the convective nonlinearity in the momentum balance equation. This radial electric field has strong shear and contributes to the saturation of the turbulence in the way shown by Biglari et al.[1] In this paper, we consider the case of resistive pressure-gradient-driven turbulence with $\omega_{*e} \neq 0$, which has been extensively studied[2,3] in the absence of ω^* effects. The numerical results for $|\omega_e^*| \lesssim \gamma_0$ indicate a reduction of the saturation level which is mainly caused by the generated sheared electric field. In the case considered, the addition of an external radial electric field, E_r of the order $\pm T_e/r$ does not affect the turbulence very much, because the final E_r is dominated by the self-generated field which is always stabilizing.

These results show that changes on turbulence level and poloidal rotation velocity are concommitant, and it can be difficult to separate what is the cause and what is the effect. The observed change in D-III-D of poloidal rotation at the L-H transition can be, in principle, either the cause for the reduction of edge turbulence and the improvement of confinement,[4] or the result of the turbulence reduction.

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CONSERVATION PROPERTIES OF A GYROKINETIC FOKKER–PLANCK COLLISION OPERATOR*

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A kinetic equation describes the time evolution of a distribution function f in phase space in terms of two operators acting on f: $\partial f/\partial t = X_h[f] + C[f]$. The first operator describes the evolution of f under the action of a Hamiltonian vector field $X_h[f] = \{h, f\}$ where h is the particle Hamiltonian function and $\{\ ,\ \}$ is the Poisson bracket. The second operator describes the evolution of f due to particle collisions in phase space. Our model collision operator is of the Fokker–Planck type

$$C[f](\mathbf{z},t) = -\frac{\partial}{\partial \mathbf{v}}\cdot \left[\mathbf{A}(\mathbf{z}) f(\mathbf{z},t) - \mathcal{D}(\mathbf{z})\cdot \frac{\partial}{\partial \mathbf{v}} f(\mathbf{z},t) \right], \tag{1}$$

where $\mathbf{z} = (\mathbf{x}, \mathbf{v})$ is a point in phase space and $\mathbf{A}$, $\mathcal{D}$ are the dynamical friction vector and diffusion tensor, respectively. The particle number conservation property of $C[f]$ follows directly from the explicit divergence form of Eq. (1). The momentum and energy conservation properties follow from the specific expressions for $\mathbf{A}$ and $\mathcal{D}$ used in Eq. (1).

The gyrokinetic formalism provides a low-frequency description of magnetized plasma behavior in terms of the guiding-center and gyrocenter dynamics. The guiding-center and gyrocenter phase-space transformations are both carried out through the use of Lie transforms. The phase-space transformation of the Hamiltonian vector field is well documented and leads to the so-called gyrokinetic Vlasov equation. In the present work, we apply Lie-transform techniques to the transformation of the collision operator $C[f]$ given by Eq. (1). We obtain an asymptotic expression for the transformed collision operator in terms of the original collision operator and the generating vector fields for the phase-space transformations. The conservation properties of the transformed (guiding-center or gyrocenter) collision operator are then investigated in detail.

The derivation of a gyrokinetic collision operator is important for gyrokinetic particle simulation studies, and provides an alternative access to classical, neoclassical, and turbulent (fluctuation-induced) transport processes.

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Passive Control of the Plasma Vertical Instability in a Single-Turn Tokamak*

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Production of a self-sustained fusion reaction requires a high-current tokamak system. Therefore, plasma current control will be a significant difficulty in a fusion ignition experiment. An efficient method to maintain a high plasma current in a tokamak is by generating a high toroidal field. Reasonable probability for fusion ignition demands fields about twice the intensity of conventional high-field tokamaks. A single-turn-coil tokamak has been proposed by Rosenbluth, Weldon, and Woodson to realize an ignition experiment along these lines of thought. The plasma column is surrounded by a massive conducting structure and an internal poloidal field system. The energy-principle analysis of tokamak vertical stability by Rutherford (1973) and Dobrott and Chang (1987) is extended to describe a single-turn-coil tokamak with elliptical cross section. The dispersion equation is solved and a typical growth time over one second is obtained. The analytical results are compared with a rigid filament numerical analysis (D. Humphreys *et al.*, 1989) and a non-rigid, MHD-consistent numerical analysis (R. Albanese *et al.*, 1989) The physical differences in the analyses are discussed. The results are of the same order of magnitude than obtained analytically. It is concluded that plasma vertical stability control is facilitated in a single-turn tokamak because of wall proximity and conformality.

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Simulations Using the Multi-Mode Transport Model*

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A selection of tokamak discharges are simulated with the 1-1/2-D BALDUR transport code using variations of the multi-mode transport model[1-3] in order to calibrate a predictive transport model for use in simulating CIT and other tokamak reactor designs. Trapped electron and η_i modes dominate in the core of the plasma while resistive ballooning modes[4] dominate in the periphery. The model is calibrated with respect to (1) the relative proportions of the different modes, (2) the transition from dissipative to collisionless trapped electron mode, and (3) the onset of the η_i mode.

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[3]J. Sheffield, "Tokamaks Transport in the Presence of Multiple Mechanisms," Nuclear Fusion **29** (1989) 1347–1372.

[4]B. A. Carreras and P. H. Diamond, "Thermal diffusivity induced by resistive pressure-gradient-driven turbulence," Phys. Fluids B **1** (1989) 1011–1017.

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Abstract for Sherwood Theory Meeting
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Gyroresonance Crossing, Quasilinear Diffusion and Conservation Laws in Axisymmetric Toroidal Plasma*

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We present a general formalism for gyroresonant absorption in axisymmetric tokamak geometry. Gyroresonance occurs locally where the (Doppler-shifted) frequency of an electromagnetic wave matches the local gyrofrequency or its harmonics. In toroidal geometry and for small amplitude waves, a particle may repeatedly cross a resonance region, each time picking up a correlated jump in its magnetic moment, toroidal angular momentum, and field line. This random walk therefore leads to quasilinear diffusion [1,2] in phase-space. By using the Lagrangian variational principle, we derive a set of self-consistent equations governing the evolution of the oscillation-center distribution, the waves, and the background field. These equations are then coarse-grained, appropriate for the irreversible (entropy-producing) gyroresonant absorption processes. The local conservation laws [3,4] of energy and momentum are also derived, and are shown to be satisfied by the coarse-grained equations. It is also shown that quasilinear diffusion produces a net electric current perpendicular to the magnetic field, which may have important consequences.

*This work was supported by US DOE under contracts number DE-AC03-76SF00098 and DE-FG05-80ET-53088.

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[2] H. L. Berk, *J. Plasma Phys.* **20**, 205 (1978) (quasilinear theory in one-dimensional slab geometry; local energy conservation).
[3] P. L. Similon, *Phys. Lett.* **112A**, 33 (1985) (variational principle and energy-momentum conservation for guiding-center plasma without waves).
[4] S. W. McDonald, C. Grebogi, and A. N. Kaufman, *Phys. Lett.* **111A**, 19 (1985) (quasilinear and wave kinetic equations; entropy production).

A 1-D Transport Code for the RFP based on a Theoretical Turbulence Model*

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A transport model for the reversed-field pinch (RFP) will be described. The transport equations are derived from a quasi-linear Vlasov formulation which allows for a self-consistent treatment of turbulence effects. A 1-D transport code based on this formulation is used to examine different theoretical turbulence models. The transport equations are averaged over the Alfvén time scale. The basic model includes classical transport (Braginskii coefficients), with selected turbulence effects.

We examine theoretical models of turbulence terms whose development is guided by the results of 3-D MHD simulations.[1] The turbulence model assumes saturated $m = 1$ kink/tearing modes with nonlinearly driven $m = 0$ modes.[2] The turbulence gives rise to a hyper-resistivity at the $m = 1$ and $m = 0$ rational surfaces, and a helicity-conserving "α-effect" in Ohm's law away from these surfaces. It has been found that the α-effect due to $m = 1$ modes has a significant effect on the nature of the reversed-field profiles. This turbulence model allows for a self-consistent treatment of field-reversal. We will demonstrate how this model produces profiles which are characteristic of RFP plasmas.

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

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Collapse of Drift Wave Vortices from Magnetic Shear*

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For drift wave vorticities in a sheared magnetic field the potential vorticity changes due to the ion acoustic flow $dv_{\|}/dt = -\nabla_{\|}(e\Phi/m_i)$ since

$$\frac{d}{dt}\left[\frac{\omega_{ci} + \nabla_{\perp}^2\left(\frac{e\Phi}{m\omega_{ci}}\right)}{n(x, e\Phi/T_e)}\right] = \frac{\omega_{ci}\,\nabla_{\|}\,v_{\|}}{n(x, e\Phi/T_e)} .$$

The vortex stretching term $(\vec{\omega}_{ci}+\nabla\times\vec{v})\cdot\nabla\vec{v} \approx \omega_{ci}\,\nabla_{\|}\,v_{\|}$ allows the local vorticity correlations of size $r_0(t)$ with $\nabla^2\Phi \cong -4\Phi_m/r_0^2(t)$ to grow while conserving the total energy $E_{d\omega} + E_{ac}$ by radiating ion waves. The result is a collapse to small scales $k_{\perp}\,\rho_s > 1$ that may compete or replace the usual mode coupling mechanism of transferring energy to large scales. The simulations show the weak vortex radiative damping theory of Meiss-Horton for $S = L_n/L_s \ll (\rho_s/r_0)^2$, and the fast (partial) collapse for large shear. For η_i modes the generation of vorticity from $\hat{\mathbf{z}}\cdot[\nabla\times(\nabla p_i/n)] = -\hat{\mathbf{z}}\cdot(\nabla n\times\nabla p_i)/n^2$ appears to arrest the collapse.

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Wave Kinetic Theory

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Plasma problems that involve electromagnetic waves of short wavelength can be most easily solved using wave kinetic theory. This theory relates the number of photons per phase space volume $\hbar J(x,k,t)$, the wave energy density $w=\omega J$, and the wave momentum density $g=kJ$ and gives an evolution, or kinetic, equation for the action density J. The basic form of wave kinetic theory is obvious by analogy to the classical limit of quantum mechanics. But, the derivation of the theory from Maxwell's equations is subtle and important for developing the theory of wave-plasma interactions. The use of complex forms for E, B, j, and ρ in Maxwell's equations allows one to dispense with the eikonal approximation. The primary purpose of the eikonal approximation is to separate the rapid oscillation of the wave from the slow variation in amplitude. In the complex representation this separation is effected using quantities of the form f^*g. If f_w and g_w are any two real quantities associated with a wave, $f^*g=2\langle f_w g_w\rangle+2i\langle \overline{f_w} g_w\rangle$ with $\langle\cdots\rangle$ an average over the phase of the eikonal and with $\overline{f_w}$ being f_w with the phase of the eikonal advanced by 90^0. The evolution equations for J, w, and g are derived using the source functions. The source functions (per unit volume) for energy and momentum are $-j\cdot E^*/2$ and $-(j\times B^*/c+\rho E^*)/2$. The source function for action is shown to be $-(j\cdot A^*+c\rho\Phi^*)/2c$ with A the vector potential and Φ the scalar potential. The real part of the energy and momentum sources is the input into the wave, but the imaginary part of the action source is the rate of action production. The derivation of the evolution equations for J, w, and g implies the relations $w=\omega J$ and $g=kJ$. The derivation is based on the Weyl representation of the electric field. The form of such derivations was pioneered by McDonald and Kaufman [Phys. Rev. A32, 1708 (1985)]. Work supported by US Dept. of Energy Grant DE-FG05-84-ER53176.

CONNECTIONS IN A HIERARCHY OF MHD MODELS

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We employ MHD models to develop a self-consistent theory of confined plasma behavior in complicated geometries like tokomaks. The nondissipative Grad-Shafranov equilibrium model lies at the lowest level in the hierarchy of models. Next in complexity is the slow-evolution resistive Grad-Hogan model. We are in the process of establishing connections between these models, both theoretically and computationally.

Our test case is a 2-D doublet simulation subjected to sinusoidally varying boundary conditions. This configuration contains the geometrical complications of a separatrix and a plasma-vacuum interface. As known from general theory of partial differential equations applied to fluid dynamics, when dissipative parameters approach zero, rapid but continuous transitions such as boundary layers and shocks develop within the fluid. These can be modeled with adiabatic equations by admitting generalized solutions which have discontinuities, jumps, across singular surfaces where the dissipation is localized. We are exploring such adiabatic modeling for MHD.

To establish the relation between the adiabatic and resistive systems, we use the profile $\mu(\psi)$ appearing in the Grad-Shafranov equations. This profile defines the thermodynamic state of the adiabatic plasma. By formally extending the expression of μ to the resistive case [Blank and Kress, 2D34, Sherwood Theory conference, Apr 1988], we get a handle to connect low-resistivity to adiabatic MHD. Using this handle, we do see the formation of a sheath around the separatrix which thins rapidly as the resistivity tends to zero [Blank and Kress, Bull. Am. Phys. Soc. **33**, 1903, (1988)]. In order to complete the connection between the two systems we are proceeding to find appropriate adiabatic profiles corresponding to low-resistivity profiles by two different approaches:

1. In the neighborhood of the separatrix, tailor the shape of a profile obtained at low resistivity to satisfy adiabatic jump conditions and asymptotic behavior. Next, verify that the resultant singular solution of the adiabatic equations approximates the low-resistivity solution.

2. Beginning with a simple adiabatic profile, modify it continuously to fit a corresponding low-resistivity profile in order to explore the range of the factors affecting the adiabatic model and, ultimately, to obtain the necessary verification of the approximation to the higher level resistive model.

Progress by both approaches will be reported.

Tearing Mode Stability in a Tokamak

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The tearing mode stability in a noncircular tokamak is studied for both the force-free and finite β cases. The stability boundary is determined for the force-free tokamak as a function of plasma elongation and current profile. It is found that a pedestal current profile remains necessary for the stability of the plasma. A model problem for the finite β tearing mode inner layer is studied numerically. The accuracy and solution requirements for the model problem are determined.

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Non-Existence of Quasi-Helically Symmetric Equilibria

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The magnetic field strength of quasi-helically symmetric stellarators is a function of the longitudinal magnetic flux and one helical coordinate alone, instead of the two angular coordinates typical of conventional stellarators. Quasi-helical stellarators have essentially the same transport properties as that of axisymmetric tokamaks. We examine the existence of quasi-helical configurations by performing a Taylor expansion in the square root of the longitudinal flux about a magnetic axis, which is equivalent to an expansion in the inverse aspect ratio ε. We equate covariant and contravariant representations of the B-field, with the longitudinal flux and the poloidal and toroidal angles forming the curvilinear coordinates. Together with the force balance equation, these equations form the constraints of general scalar-pressure MHD equilibria. We prove that the field strength cannot be made to be constant on a flux surface. We try to impose the quasi-helical constraint order by order in the expansion and prove that the quasi-helical symmetry is broken by terms of order $(\Delta B)/B \approx \varepsilon^3$, so that quasi-helical stellarators do not exist. However, quasi-helical symmetry can be approximated quite well for large aspect ratio configurations, as was shown computationally by Nührenberg and Zille [1].

We acknowledge support from the U. S. Department of Energy under grant #DE-FG05-84ER53176.

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Suggested Tokamak Parameter Regimes

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An important feature in the preliminary design of future tokamaks is to determine the parameter regimes in which the ideal magnetohydrodynamic (MHD) properties are most favorable. In particular, it is necessary to determine the dependence on aspect ratio, elongation and triangularity of maximum stable β to $n = 1$ modes with a wall at ∞. Stability to $n = 1$ modes with a wall at ∞ normally guarantees ballooning stability and stability to higher number low n modes. An ideal MHD equilibrium and stability computational study has been done, the end result of which is an understanding for next generation tokamaks of trends in $n = 1$ stability with a wall at infinity for varying elongation, aspect ratio and triangularity. The following constraints were imposed; $\ell_i = 0.8$, $q_0 = 1.05$, $q_\ell = 3.5$, and the toroidal magnetic field B_T was held constant at 4.0 T. Given these constraints, an appropriate range in aspect ratio, elongation and triangularity was selected. Here the range was R_0/a between 2.0 and 6.0, κ between 1.6 and 2.4 and δ between 0.4 and 0.6. Once the marginal equilibria was obtained, the $n = 0$ stability was determined with a wall at 1.6. On the basis of this numerical ideal MHD equilibrium and stability study done in the first stability regime and work done in the second stability regime, reported in other papers, we recommend, for future tokamaks, parameter ranges in aspect ratio, elongation and triangularity which have favorable ideal MHD equilibrium and stability properties. These parameter regimes are further refined by determination of the ease of control of plasma cross-sectional shape in the various regimes [1,2].

[1] F.J. Helton *et al.*, Comments on Plasma Physics and Controlled Fusion **XI** (1987) 127.

[2] F.J. Helton *et al.*, General Atomics Report GA-A19323 (1988), submitted to Nucl. Fusion.

Abstract Submitted for the 1990 Sherwood International Fusion Theory Conference.
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23-25 April 1990

Magnetohydrostatic Equilibria and Force-Free Fields. N.A.SALINGAROS, University of Texas.---The applicability of the usual force-free model in describing laboratory plasmas is critically re-examined. It is shown that plasma equilibrium cannot be deduced from a local equation in the magnetic field alone. Three major revisions in the usual theory follow: (i) The magnetic field in many assumed "force-free" configurations is habitually miscalculated; in particular, a hitherto unsuspected Lorentz self-force exists in the Bessel-function model for the Reversed-Field Pinch. (ii) In order to accommodate this additional force, the standard model for the Reversed-Field Pinch reverses its description of the plasma from paramagnetic to diamagnetic. (iii) Lorentz force-free plasmas are in a marginally stable state because they do not correspond to a state of minimum magnetic energy. It is widely misunderstood that the opposite is true.

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On The Importance of Neutrals in Ion Thermal Transport Studies*

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Although the neutral density in the interior of a tokamak is small, the charge exchange losses from it can be large enough to contribute significantly to the ion power balance. We have done a detailed study of the full neutral density profile in TEXT using a diagnostic neutral beam with a radially scanning neutral energy analyser, H_{α} profile measurements, and various neutral codes such as ANTIC and NUT. A variational estimate of the ratio of ion heat flux from charge exchange to the neoclassical flux is also presented in another poster at this meeting[1]. We find that at low densities (below ~ 3×10^{13}), where the electron temperature is sufficiently above the ion temperature to permit ion power balance studies, the neutral charge exchange losses are dominant. Within the error bars set by the neutral measurements, the measured ion thermal transport in the bulk of the plasma in TEXT is consistent with neoclassical theory.

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1. R.D. Hazeltine, P. M. Valanju, and E. Solano, poster at this meeting.

Abstract submitted to the
1990 International Sherwood Fusion Conference
April 23-25, 1990, Williamsburg, VA

RADIATIVE CONDENSATION INSTABILITY IN A TOKAMAK EDGE PLASMA

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The short scale length fluctuations at the edge, which typically have high poloidal mode number (m ~ 100), have been studied by Drake, et al.[1] in slab geometry with homogeneous plasma in a sheared magnetic field. We have extended the linear evolution of these fluctuations using ballooning mode formalism. Included are: non-uniform plasma, Pfirsch-Schluter perpendicular ion thermal conductivity and asymmetric anomalous electron perpendicular thermal conductivity. It is shown that the theory can explain localization of the fluctuations on inboard side of tokamak as observed experimentally.[2] Details of the calculations will be presented.

[1] J.F. Drake, L. Sparks, and G. Van Hoven, Phys. Fluids 31, 813 (1988).
[2] S.J. Zweben and S.S. Medley, Phys. Fluids B1, 2058 (1989).

SHERWOOD THEORY MEETING 1990

Nonlinear Interaction of Tearing Modes in the Presence of Equilibrium Shear Flow*

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The interaction of two near marginal tearing modes in the presence of shear flow is studied by using bifurcation theory. Upon incorporating center manifold reduction, the original partial differential equations can be reduced to a four-dimensional system of ordinary differential equations. For the case without flow, these amplitude equations are invariant under rotation and reflection transformations, due to the $O(2)$ symmetry of this physical problem.[1] The presence of flow breaks the reflection symmetry, while the rotation symmetry is preserved. The bifurcated solutions of traveling and modulated waves are found. Thus, an explanation is given for the oscillating island structure observed in the numerical computations of Persson et al.[2,3]

1. Rainer Grauer, Physica D **35**, 107 (1989).
2. M. Persson, Ph.D. thesis "Resistive MHD Stability for Rotating Plasmas," Chalmers University of Technology Technical Report No. 177 (1987), Göteborg, Sweden; M. Persson and A. Bondeson, Australian National University Report ANU-PRL-TP90/1 (1990), Canberra, Australia.
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Theoretical Problems of Direct Relevance to ITER*

W.M. Nevins and the ITER Team

The U.S. magnetic fusion program has been focused on the development of fusion power as a commercial energy source. If we are to maintain our credibility as an energy development program the magnetic fusion community must decide soon on the design and construction of new experimental facilities that will advance our program toward a fusion demonstration reactor on a reasonable time scale. The International Thermonuclear Experimental Reactor (ITER) could provide much of the physics and technical data needed for a demonstration reactor. The ITER conceptual design effort has been proceeding for two years. While most areas of plasma physics have some impact on the ITER design, there are two areas where further progress is particularly important. These are confinement and the physics of scrape-off-layers.

Confinement sets scale of machine. Also, better understanding of energy confinement is needed to adequately analyze thermal instabilities and plan for burn control. The confinement of fuel ions and impurities determines the burn-up fraction (which tends to be low), and through this the tritium inventory of the fueling system (which tends to be high). The consequence of the most dangerous accident (release of this tritium inventory) can be greatly reduced if the tritium inventory in the fuel processing system is kept down.

Scrape-off-layer (SOL) physics is as important as transport. With diverted plasmas the area available to take the alpha particle heating power tends to scale like the surface area, while the fusion power increases like the volume. Hence, the peak power load on the divertor plate increases with machine size. ITER is already at the limits of current technology, and does not have the power density required for a fusion power reactor. If fusion power reactors prove not to be possible, it will be because there is no acceptable operating window between the large machine required for energy confinement and the limits on power loading imposed by the divertor. The theory community is working very hard to improve our understanding of one half of this problem. More effort is needed on the other half (understanding SOL physics so that we can make more reliable predictions of peak power loads on the divertor, and learn to change plasma conditions to mitigate the divertor heat load).

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Collisionless Two-Fluid Model of Curvature-Driven Ion-Temperature-Gradient Transport *

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A generalization[1] of the Chew-Goldberger-Low[2] theory to include the full heat flow balance and the reducible parts of the fourth-order velocity moments is developed and applied to derive the fully nonlinear dynamics of the electrostatic ion-temperature-gradient transport driven by ∇B and magnetic field curvature.

It is shown that in the relevant collisionless domain, and subject to the conditions of localization of the ions perpendicular ($k^2\rho^2 \ll 1$) and parallel ($\omega/k_{\parallel} \gg C_s$) to the magnetic field, there are two relevant heat flow vectors associated with the flow of perpendicular and parallel contributions to the thermal kinetic energy, respectively. In the absence of the irreducible part of the fourth-order velocity moments (i.e., the part left over after decomposing these moments into lower-order ones), both heat flow vectors consist of drift-heat flux type contributions plus curvature-drift corrections. Such an irreducible part is linearly only due to wave-particle interactions, and is neglected here. The system thereby truncated is to be viewed as the 16-moment analog of the 13-moment method[3] for collisional systems. The gyro-viscous and polarization fluxes are also derived, including the contributions to the former by the heat flow.

The linear threshold η_i is given to lowest order in the FLR parameter as a function of L_n/R_c and T_e/T_e, and compares well with kinetic theory.

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* Work performed under the auspices of the USDOE

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1 J. P. Mondt and J. Weiland, Los Alamos National Laboratory report LA-UR-89-3678, 1989.

2 G. F. Chew, M. L. Goldberger, and F. E. Low, *Proc. Ryo. Soc.* **A236**, 112 (1956).

3 H. Grad, Thermodynamik der Gase, Handbuch der Physik, Springer-Verlag, Berlin 1958, Bd. 2.

EFFECT OF TOKAMAK ELECTROSTATIC EDGE FLUCTUATIONS ON ORBITS AND TRANSPORT*

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Here we focus on fluctuations, as observed in TEXT, which are localized to the edge, have frequencies comparable to the D.C. poloidal $\mathbf{E} \times \mathbf{B}$ precession frequency, and have short poloidal and radial wavelengths. These wave properties allow one to deduce many of the major effects on single particle orbits analytically, and from this information make estimates of effect on transport. These estimates, as well as numerical calculations of the effect of edge fluctuations on direct convective losses, will be presented.

Because of the shortness of the wavelengths, particles typically traverse a wavelength in a time short compared to a fluctuation period. A consequence of this is that the guiding center energy (as well as the magnetic moment and canonical momentum) is approximately conserved on the short time scale. This allows one to visualize particle behavior and quickly make estimates of particle orbit properties. For example, linearized analysis yields very simple expressions for the deviations from the unperturbed orbits produced by the fluctuations. These expressions are in reasonable agreement with both resonant and non-resonant behavior observed numerically.

We have also calculated the short time scale average of the lowest order non-linear corrections to the orbits. The linear and non-linear expressions show strong dependence on the D.C. and fluctuating electric field for ions, but not for electrons. Using the linear and non-linear orbit expressions, we have made estimates of the effect of modest fluctuating fields on diffusive neoclassical transport. For the highly localized modes, such as observed in TEXT, the nonlinear approach leads to larger diffusive transport for ions.

The full non-linear analytic considerations allow us to put bounds on the effect of fluctuations on direct convective losses. This is quite useful because all the statistical properties of the fluctuations, such as local correlation lengths, are usually not known. The numerical calculations reveal that the edge fluctuations make modest changes in direct convective losses, except in the region where the edge fluctuations are strong. This is important because the direct convective losses for ions can be a dominant loss mechanism in the outer 10% to 50% of the plasma volume.

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Gyrokinetic Simulation of Energetic Particle Effects on Tokamak Stability*

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The confinement and stability influence of fusion produced energetic particles are critical issues in the design of advanced tokamaks that sustain ignition. Low frequency fluctuations, such as drift waves and ballooning modes, can be excited by the presence of energetic particles. Theoretical investigations of these low frequency modes are either based on analytic approximated solution of the gyrokinetic equation or numerical particle simulation technique. A new approach is proposed here by solving the gyrokinetic equation directly. The advantage of this approach is the inclusion of many important kinetic features of the problem without approximations and it provides a low noise alternate to the particle pushing codes.

As an example of this new simulation technique, the ion temperature gradient mode with energetic particle is investigated. The gyrokinetic equations for the background ion and the energetic particles are written in the time domain. The electron response is assumed to be adiabatic. Ballooning mode representation is employed to reduce the system to a one dimensional spatial problem in the extended poloidal angle variable. The ions distributions are followed in time development from given initial distributions by solving the time dependent gyrokinetic equations with a partially implicit scheme. The velocity space variables are passive parameters in a collisionless model. Quasi–neutrality condition and the Ampere's law are used to solve for the perturbed electromagnetic fields. For unstable modes, the distribution functions will eventually develop to a definite steady growth state independent of the inital distributions. Both the linear growth rate, the eigenfrequency and eigenmode structure can be determined at this stage. Detailed results of the electrostatic and electromagnetic instabilities of the ion temperature gradient mode will be discussed.

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MODELING OF FLUCTUATIONS AT THE EDGE OF THE TEXT TOKAMAK*

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Three-dimensional nonlinear computer calculations based on the thermally driven convective cell turbulence model with pressure balance[1] and using the resistive MHD code KITE,[2] have been successful in reproducing some of the features of the fluctuations at the edge of the TEXT tokamak.[3] Results obtained by breaking pressure balance and implementing evolution equations for the density and parallel velocity show that the condensation component contributes little to the growth and saturation level of the fluctuations as compared to the thermal component of the impurity radiation drive.[4] As the loop voltage is taken to zero, the rippling mode fades away and the remaining instability is a thermally driven drift wave.[5] This limit is applicable to edge current-free TEXT discharges and currentless configurations like ATF. Preliminary linear and nonlinear results indicate that growth rates and fluctuation levels can be comparable to those obtained for thermally driven convective cell turbulence. Effects of other components of the impurity drive such as ionization and charge exchange, as well as collisional and impurity drift wave models of edge turbulence, will also be reported.

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FLUIDLIKE STUDIES OF THE SHEATH AND PRESHEATH REGIONS OF A PLASMA*

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We investigate the problem of a collisional plasma flowing into a perfectly absorbing wall. Both the collisional presheath and the collisionless sheath regions are modeled by fluidlike moment equations that are derived from kinetic theory. Previous work has been based primarily on the collisional Braginskii equations[1] or collisionless kinetic theory.[2] The electron distribution function is obtained from the solution of a Pastukhov type problem.[3] For the ions a kinetic theory is required to determine the ion viscous stress tensor because the collisional mean free path is comparable to the characteristic scale length in the presheath region. A boundary layer analysis is applied for determining the distribution function of the ions in the velocity space region corresponding to no net return flux from the wall. The viscous force deduced from this distribution, which is a cutoff Maxwellian relaxed by collisions, is dominant in the region closest to the sheath region and removes singularities between the presheath and the sheath regions. Numerical calculations for the densities, electron and ion flow velocities and potential of the overall presheath with and without the viscous force will be presented. Also, numerical results obtained with the Braginskii viscous force will be compared against those with our boundary layer viscous force.

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Turbulence and Transport Simulations for Experimental Parameters Using the Kinetic δf Particle Algorithm*

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The δf particle algorithm[1] has been implemented for the ion gyrokinetic equation. The resulting code is capable of 3-d simulations of η_i instabilities for realistic experimental parameter ($\eta_i \sim 2$, $L_s/L_n \sim 10$, $\rho_i/L_n \sim 10^{-3}$), with runs into nonlinear saturation requiring tens of minutes of Cray CPU time. The code currently uses an adiabatic electron response and slab geometry, but can be generalized easily. To examine the accuracy of the algorithm, simulations will be presented and compared with results of other codes, and with tokamak data for several well-diagnosed shots. Comparisons with a finite difference grid code[2] and a standard particle algorithm[3] demonstrate accuracy and enormous savings in computer time. Accuracy is also tested using physical energy conservation relations. In addition, simulations are presented in which parameter values such as η_i, L_s/L_n, ρ_i/L_n and T_i/T_e are the same as in several tokamak discharges; results for the saturated spectrum and ion heat flux are compared with the experimentally obtained values.

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Operational Conditions for an Ignition Experiment*

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The conditions required for a fusion ignition experiment are investigated. A general approach to DT ignition conditions is illustrated in a ($n\tau T$, T) diagram. A discussion on access to ignition independent of specific energy confinement scaling expression is presented. It is argued that the low beta, L-mode, ohmic heating regime is the most desirable regime to realize a self-sustained fusion reaction. The most efficient path to ignition conditions seems to be the low plasma temperature regime.

* Work supported by the Texas Atomic Energy Research Foundation.
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CONVERSION OF 3-D VMEC CODE OUTPUT INTO 2-D STEP CODE INPUT FOR STABILITY STUDIES OF GENERAL CONFIGURATIONS

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The periodicity associated with there being a finite number of helical field periods in a stellarator makes equilibrium studies of fully three-dimensional configurations feasible. Although stability studies with respect to modes that do not possess this periodicity can be done, they are difficult. On the other hand, two-dimensional averaged codes should be good for survey studies of these stability properties. This is because the physical assumptions, namely the elimination of the fast magnetosonic modes and the decoupling of modes with different toroidal mode numbers, that are made in the process of averaging over the field periods in the development of such models, apply well in general configurations. This has led us to develop techniques[1] to manipulate the output from the 3-D VMEC code[2] into a form where it could be used as input for the 2-D STEP code.[3] We have been working on this problem for some time. In this paper, we describe the progress we have been making in this program, including the implementation of an improvement to the original STEP stability code.

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The Axial Mode Revisited*

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It has been speculated that an axial TEM mode may propagate around a tokamak in the tenuous plasma between the vessel wall and the high-density reactor plasma[1], though little work has been done on this mode. The existence of the mode has also been called into question[2]. This mode will be investigated by numerically constructing wave solutions of the cold plasma model in slab geometry (but propagating obliquely to the magnetic field), and examining the damping length due to resonant absorption and fast wave leakage. The plasma density profile will be smooth, and an outgoing wave boundary condition will be imposed on the fast wave in the dense plasma. If time permits, other surface waves will also be investigated.

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Suppression of Magnetic Islands by Energetic Ions in Toroidal Plasmas

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We propose that the size of a magnetic island in a toroidal plasma can be reduced drastically by introducing energetic ions via parallel neutral-beam injection. The method can be used to suppress major disruptions triggered by the nonlinear growth of m = 2, n = 1 islands in a tokamak, and to control the size of vacuum islands caused by field errors in a stellarator.

The physical picture is simple:[1] we show that in the Rutherford regime, the effect of energetic ions, injected nearly parallel to the magnetic field, depends crucially on the local ion-density profile. In a tokamak, the size of a m = 2, n = 1 island at saturation can be made very small by having the energetic ion density profile peak just outside the q = 2 surface. The analytical calculation uses kinetic theory, and includes the effects of bootstrap currents[2,3] and resistive interchange effects.[4] The energetic ions must satisfy the inequality $|x_*| > w_s$ where $|x_*| \sim \varepsilon q v_{\|h}/\Omega_i$ and w_s is the saturated island width. (Here ε is the inverse aspect ratio, q, the safety factor, $v_{\|h}$, the hot-ion parallel velocity and Ω_i, the ion cyclotron frequency.) Analytical estimates indicate that if 40 keV protons with a local density $n_h \sim 10^{12}$ cm^{-3} are deposited just outside the q = 2 surface with a density scale-length $L_h \sim 6$ cm via parallel neutral-beam injection, the m = 2 island saturates at a width $w_s \lesssim 1$ cm. The power expended is typically a small fraction of that required for Ohmic or neutral-beam heating of the bulk plasma.

The application of the analysis to stellarators was stimulated by the observation of large vacuum islands in ATF, and requires an extension of the theory to the range $|x_*| < w_s < a$ where a is the minor radius . In this range, the hot-ion density is assumed to be arranged so that the dominant part of the island current comes from the ions trapped in the magnetic islands. (In the range $|x_*| > w_s$, the picture given above for tokamaks essentially carries over, but must be modified to include the effects of a vacuum magnetic well / hill.) Our estimates indicate that large vacuum islands can be reduced by as much as one-half of their orginal size by using energetic ions.

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DISSIPATIVE STRUCTURE IN PLASMA TURBULENCE

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A new enhanced radiation process from plasma turbulence (plasma-maser) is interpreted as "dissipative structure" in plasma turbulence. The plasma-maser process is effective in an open system where some of the input energy is dissipated as anomalous radiation. The validity of the quasilinear theory which neglects the second order electric field is given under the random phase approximation. The ordinary mode growth rate in the presence of the enhanced stationary Langmuir turbulence is obtained and the results have potential importance to clarify the mechanism of the anomalous radiation in laboratory and space plasmas.

Fluid Models for Landau Damping and the Ion Temperature Gradient Instability

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An algorithm to model kinetic Landau-damping processes in a fluid equation representation is developed. A simple model is obtained by starting with the usual equations for the first three fluid moments (density, momentum, and pressure), and closing the heirarchy by assuming that the heat flux can be written in the form

$$q_k = -n_0 \chi_1 \frac{2^{1/2} v_t}{|k|} ik\tilde{T}_k$$

in Fourier wavenumber space, where n_0 is the unperturbed density, $\tilde{T}$ is the perturbed temperature, $v_t = (T_0/m)^{1/2}$, and χ_1 is a dimensionless parameter which best replicates Maxwellian Landau damping when $\chi_1 = 2/\sqrt{\pi}$. In real space, the heat flux takes a convolution form $q(z) = -n_0 \int dz' \tilde{\chi}(z') \tilde{T}(z+z')$, but its simple wavenumber representation will be useful for spectral numerical algorithms.

This closure approximation yields a 3-pole approximation to the plasma dispersion Z-function for a Maxwellian $f_0(v)$. Alternatively, it is identical to the kinetic response for an $f_0(v)$ which is close to Maxwellian but which decreases like $1/v^4$ for large v. This closure is also extended to a four-moment fluid model which provides an even better 4-pole fit of Maxwellian Landau damping, and is equivalent to an $f_0(v)$ which decreases like $1/v^6$ for large v.

The Ion Temperature Gradient (ITG) instability is studied using kinetic equations and fluid equations in a simple unsheared slab without finite gyroradius effects. Previous fluid models lead to errors in the stability threshold and growth rate because they relied on a parallel viscosity to model Landau damping, which corresponds to an $f_0(v)$ with a $1/v^2$ (or $1/|v|^3$ in some models) asymptotic dependence and hence a divergent pressure moment. The present algorithm reproduces the proper threshold and growth rates for ITG instabilities and should be useful in extending computational studies of ITG turbulence closer to marginal stability, the regime relevant to most experiments.

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One-and-a-Quarter Dimensional Transport in the Presence of the Collisional Velocity-Space Particle Loss in Field-Reversed Configurations

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ABSTRACT

The loss-cone like scattering in velocity space, namely, the collisional velocity-space particle loss (VSPL)[1] has been identified as an important loss mechanism in field-reversed configurations (FRCs). As with a loss cone in velocity space for simple mirrors, the loss region in velocity space for FRCs has important effects on plasma behavior. As for the classical transport, a one-and-a-quarter dimensional transport,[2] which includes the radial transport as well as some two dimensional effects for field-reversed configurations, has been developed. In this study, the collisional VSPL is incorporated into the one-and-a-quarter dimensional transport code to study the transport effect of the VSPL mechanism. Finite-loss time of the unconfined particles is considered; both the open-field and closed-field confinement criteria are used to calculate the loss boundaries in velocity space. The effects of the collisional VSPL on the plasma transport are studied and some results from the code simulation will be presented.

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THE INTERNATIONAL SHERWOOD THEORY MEETING
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Electrical Conductivity in Tokamaks Modified by Electrostatic Trapping in the Applied Electric Field*

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Passing electrons traveling in the same direction as the applied Ohmic electric field, near the trapped-passing boundary, can get electrostatically trapped by the applied Ohmic potential, reverse their parallel flow direction, and become passing particles traveling in the opposite direction. The number of these electrons is proportional to the applied voltage and is small. But, the amount of change in their time-averaged parallel velocity, by reversing their flow direction, is about twice the average parallel velocity of the barely passing electrons and is large. Hence, these electrostatically trapped particles can significantly contribute to the Ohmic electrical current. The new electrical conductivity is calculated in the banana regime using a pitch angle scattering operator, and the values are found to be about 30% closer to the Spitzer conductivity than those from the previous neoclassical theories.

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Scattering and Localizability of ECH Power in CIT*

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The low-frequency drift-wave density fluctuations that are present in all tokamaks act to scatter a portion of the electron-cyclotron heating (ECH) power. For magnetic fields, densities, and temperatures planned for the Compact Ignition Tokamak (CIT), the scattered fraction of the incident power and the distortion of power-deposition profiles are calculated. Sensitivities are determined to the amplitude, radial profile, and spectrum of the density fluctuations and to the radial profile of the equilibrium density.

For the applications of sawtooth and tearing-mode suppression, localized heating near the $q = 1$ and $q = 2$ surfaces is required. Estimates of achievable localizability are made with realistic Gaussian beam profiles and equilibrium magnetic fields. Electron-cyclotron absorption is calculated in the weakly relativistic approximation.[1] The spreading of power-deposition profiles by density-fluctuation scattering is assessed.

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THE PHYSICS OF NONNEUTRAL PLASMAS IN TRAPS *

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We have recently initiated a program of research in an area of potential interest to the Laboratory, the confinement and trapping of nonneutral plasmas. We shall summarize this incipient research that includes the first analytic calculation that addresses the effect of the shape of a uniform density, zero-temperature charge distribution of finite extent on the electrostatic potential required for its confinement in a uniform magnetic field. This study motivated our interest in writing a fourth-order Runge-Kutta scheme for calculating the three-dimensional molecular dynamics of the charges in a Penning trap. Additionally, we have constructed a novel numerical scheme for calculating the crystal structure of the trapped strongly-coupled nonneutral plasma. The current status of this research will be delineated.

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Numerical Reconstruction of Equilibria from Measurements of Tokamaks Operating at the Poloidal Beta Equilibrium Limit*

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As has been long recognized, a tokamak has an equilibrium poloidal beta limit beyond which flux surfaces open and confinement is lost[1,2]. The precise relationship between the maximum poloidal beta, the plasma current, aspect ratio and cross section is still not well known, and more theoretical work continues to be pursed [3]. Because of a "reverse bias" (or "theta-pinch") start-up technique, the HBT experiment has been used to study short-lived tokamak discharges near the poloidal beta limit [4]. This start-up procedure is non-flux-conserving, since the plasma pressure is determined by the magnitude of the theta-pinch currents while the plasma current is independently set by the ohmic transformer. HBT's primary diagnostic for the equilibrium limit came from an internal magnetic probe. When a discharge is created below the equilibrium limit, the probe clearly shows quasi-stationary closed flux surfaces with a large, outward Shafranov shift. When the plasma pressure is increased beyond the equilibrium limit, either the plasma strikes the outside wall of the vacuum vessel or, by increasing the vertical field strength, a separatrix enters the inside of the plasma destroying confinement. Recently, TFTR has also operated at the equilibrium poloidal beta limit by injecting high power neutral-beams into a low-current discharge [5]. In these experiments, $\varepsilon\beta_p > 1$, and the penetration of the separatrix into the plasma could be seen visually and with other diagnostics.

In this poster, the effectiveness of a numerical technique to reconstruct the free-boundary equilibria of these high poloidal beta discharges from experimental measurements is presented. This technique has been used previously to analyze the stability of HBT's lower β_p discharges [6], but, at high $\varepsilon\beta_p$, the reconstruction is highly non-linear. Comparisons between exact equilibria and those reconstructed numerically will be made. The magnitude of the uncertainty of the experimentally-determined $\varepsilon\beta_p$ at the poloidal beta limit and the factors determining the accuracy of the estimation of the central safety factor will be discussed.

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SHERWOOD THEORY MEETING 1990

A Portable Implementation of the Reduced MHD Equations*

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We have developed a portable implementation of the low beta reduced MHD equations. The program was originally designed to execute in parallel on a network of T800 transputers and uses a somewhat novel spectral-spline method which minimizes the work in the distributed matrix transpose operation, the key operation which converts an otherwise serial algorithm into a parallel one. The code is written in ANSI standard C and has been compiled and executed on a number of computer systems including a Macintosh II, the NeXT, a T800 transputer array, and the Cray 2. The program was ported to the Cray 2 using the new ANSI compiler. There were essentially no changes required to move the code from the transputers to the Cray, however, there was not much improvement in speed either. Reorganization of some arrays at the cost of some intermediate storage significantly improved the execution of the most important loops. These changes only modestly affected the performance on the T800s.

This code now provides a significant scientific calculation which can be used to compare the performance of a range of computational environments and to compare the cost effectiveness and throughput of local dedicated parallel arrays, workstations, and multi-user supercomputer systems. We also compare the ease of development and maintenance of the different systems. The program is being extended to a kernal/interface design which will allow distributed operation.

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The Stabilization of the $\ell = 2$ Instability in Hollow Nonneutral Plasmas by Means of Oscillating Electric Fields

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If high-frequency oscillating electric fields are applied to nonneutral plasmas, their dynamical properties can be substantially modified. A similar effect is observed in the familiar dynamic pendulum where the point of support of a rigid-rod pendulum is vibrated rapidly. A separation-of-timescales analysis similar to that used for the dynamic pendulum predicts that the frequencies of all modes in infinitely long nonneutral plasmas can be shifted. Of particular interest, however, is the prediction that the $\ell = 2$ instability that plagues hollow nonneutral plasmas can be stabilized by the application of such fields. This prediction has been verified by a two-dimensional fluid simulation. Both the analytic work and the simulation will be discussed.

Anomalous Transport of Fast Alphas

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Fusion borne α particles may not be perfectly coupled to the bulk plasma through the collisional slowing down process. Here we investigate the kinetic theory origin of possible losses and the power balance for the case $\eta_\alpha < 1$ where the coupling parameter $\eta_\alpha \equiv P_{fusion}/\frac{n_e^2}{2}\langle\sigma_f v\rangle E_{\alpha o}$, and P_{fusion} is the power actually coupled into the plasma. On a generic level, η_α can be expressed through an α loss frequency ν_L in the α kinetic equation. For $\nu_L \tau_{SD}/3 > 1$ the standard slowing down distribution $f_{SD} \sim (v^3 + v_c^3)^{-1}$ is destroyed leading to other consequences for quantities relying on the usual f_{SD}. For a given $\nu_L > 0$ and thus $\eta_\alpha < 1$, at constant $n\tau T$, the thermonuclear Q is reduced but $Q \geq 5$ operation may still be possible. As a specific example for ν_L we show results from low mode number finite amplitude Alfvén gap mode fluctuations and delineate the stable operating parameter regions for burning plasma experiments.

Enhanced Transport and MHD Stability in Tokamaks*

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We have developed a magnetic helicity conserving, mean-field model to simulate tearing modes in tokamak plasmas. In mean-field theory, coefficients which model enhanced transport processes due to fluctuating magnetic fields are introduced into the MHD equations. Our model contains: (1) an Ohm's law with a Spitzer resistivity and an electron current viscosity, and (2) an electron heat equation with a drift wave turbulence term and an enhanced electron thermal conductivity. The current viscosity and enhanced thermal conductivity are linearly related to each other, and are due to the local destruction of magnetic surfaces. Magnetic surfaces are destroyed when fluctuations in the magnetic field alter the local field line topology, allowing field lines to wander stochastically over a region of space. Stochastic wandering of field lines is expected to occur near the separatrices of structures called magnetic islands. In our model, it is the locally stochastic nature of the magnetic field which enhances transport processes. In order to conform to the enhanced transport, plasma profiles develop plateau regions in the vicinity of magnetic islands. This effect stabilizes the magnetic fluctuations and provides a mechanism for the saturation of tearing modes. The resulting plasma profiles are MHD marginally stable. Using computer simulations, we are calculating self-consistent, steady-state profiles for plasma quantities using parameters from the Alcator-A tokamak. We present two studies: (1) we hold the total current fixed and vary the average particle density, and (2) we fix the average particle density and vary the total current.

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A Deterministic Particle Method for Collisional Equations*

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A particle scheme has been devised for treating the collisional term in a kinetic equation. The scheme is based on the definition of "flux" associated to the collisional term and is fully deterministic. A triangulation is used for constructing a quadrature formula that has the particles as nodes. The method is compared to the exact solution and to Monte-Carlo calculations for some model equations.

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Nonlinear Pressure Driven Resistive Modes in Tokamaks*

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We use the three-dimensional nonlinear toroidal MHD code, *MH3D*,[1] to study the nonlinear developement of pressure driven resistive modes in tokamaks. The *MH3D* code solves the full MHD equations in toroidal geometry, and can treat a shifted coordinate origin and shaped plasma boundaries using conformal coordinates.

We find that at small values of $\epsilon\beta_p$, the nonlinear effect of pressure on resistive low m modes can be either stabilizing or destabilizing depending on the equilibrium profile. For larger values of $\epsilon\beta_p$, pressure is generally destabilizing. Our nonlinear calculation starts with small but finite magnetic islands for a given mode. This is to avoid the Glasser, Green, Johnson type of linear stabilization effects for a favorable D_R. Realistically, this linear effect will be compromized due to inherent magnetic perturbations such as error fields.

For Supershot type plasmas, pressure driven resistive modes generate many small magnetic islands which fill a large portion of the plasma. (These islands sometimes overlap to produce substantial stochastic regions). These magnetic islands produce spiky pressure profiles which is similar to the ones obtained from TVTS measurement. Another effect seen in the simulation is that as $\epsilon\beta_p$ increases, the ratio between 3/2 and 2/1 modes amplitude also increases, possibly explaining the 3/2 dominant dischages often seen in TFTR.

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Renormalization Group Analysis of Alfvén Turbulence in Reduced MHD *

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Alfvén wave turbulence occurs in magnetized plasmas both in the laboratory and in space. As is often the case, the effect of turbulent small scales on the large scale dynamics can be expressed in the form of "renormalized" transport coefficients; in this case renormalized viscosity and resistivity. One recent method for calculating these renormalized quantities for Navier-Stokes turbulence is the so-called "Dynamic Renormalization Group".[1,2,3] In the present work this technique is applied to the equations of reduced MHD for Alfvénic turbulence in the presence of a strong uniform magnetic field. This provides a relation between the "turbulent β", (defined as $\langle v_\perp^2 \rangle / \langle B_\perp^2 \rangle$), and the turbulent Prandtl number, (defined as the ratio between the resistivity and the viscosity), at the fixed point of the renormalization group. The scaling behavior of the renormalized viscosity and resistivity can also be found once assumptions are made about the the form of the Alfvén wave energy spectrum.

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Nonlinear Ion Mixing Mode Particle Flux in Electron Trapping Regimes

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Steady State and Transient transport analyses of tokamak discharges typically require an inward particle pinch in order to reproduce observations. An inward component of the particle flux is particularly necessary in core regions, where the ionization source is weak, in order to balance outward diffusion. One mechanism capable of producing a pinch is the ion mixing mode[1], an extension of ion temperature gradient turbulence which incorporates nonadiabatic electron density dynamics. This mechanism produces significant inward flux components in regimes with fluid-like electron response, i.e., no trapping ($\upsilon_* > 1$), and in the collisionless trapped electron regime ($\upsilon_* < 1$, $\omega_* > \upsilon_e$)[2]. In the dissipative trapped electron regime, the quasilinear flux is entirely outward.

Here, we extend the quasilinear analysis to include resonance broadening in the electron dynamics and broadened frequency spectrum linewidths. The latter is incorporated by modeling the spectrum with a finite width and nonlinear shifts calculated from ion incoherent emission physics. It is found that finite electron-wave resonance widths and spectrum linewidths do not directly affect the sign of the particle flux. Rather, nonlinear frequency shifts, both of the electron-wave resonance frequency and the peak of the frequency spectrum, are required to produce inward flux components. These are shown to depend on details of the spectrum. Likewise, the source renormalization or beta term, which depends on the correlation of the potential with the particle distribution, can give rise to inward directed components of the radial particle flux. For $\beta < \omega_*$, this contribution is calculated explicitly. These results underscore the need for better understanding of the frequency spectrum.

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Time Dependent Effects and the Current Ramp Phase in D-T Ignition*

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The process of reaching deuterium–tritium fusion ignition conditions is strongly influenced by the nonsteady state, dynamic character of the plasma system [1]. In fact, toroidal ignition experiments that are presently proposed do not achieve true steady state conditions even in the absence of the sustained temperature rise necessary to reach burning conditions. The initial, current ramping phase of the plasma discharge can contribute significantly to the increase in the plasma temperature. Its effects on the heating to ignition are studied in a toroidal, high field ignition experiment, using the free boundary TSC code [2]. The technique of growing the plasma during the current rise is used to maintain peaked, monotonic toroidal current density profiles. The effects of simultaneously controlling the plasma density are also considered. The conditions that obtain near the end of the current ramp, including a characteristically hollow plasma loop voltage, are then used to provide accurate initial conditions for fixed boundary transport codes that model the next phase of the discharge and their effects on ignition are discussed.

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

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Current Flow in the B2 Edge-Plasma Code *

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We have modified the B2 code [1] to include net electrical current flow along field lines. These currents arise naturally due to temperature asymmetries [2] in diverted tokamaks such as DIII-D where divertor plates are electrically grounded. Experiments in DIII-D with active control of such currents by electrical biasing of the divertor plates are scheduled to occur in the next few months.

The current flow has several effects including modification of the sheath potential drop at the divertor plates, introduction of an ohmic heating contribution to the electron energy balance, and alteration of the magnetic geometry due to poloidal and toroidal components of the current flow. The first two effects are included in our code modifications, but the latter effect, which could shift the position of the the x-point and the separatrix strike points on the divertor plates, is not. The electrostatic potential on open field lines is obtained from the electron momentum equation or Ohm's Law, including both thermoelectric and friction terms. For biased divertor plates, the current on each flux tube is adjusted so that the calculated potential difference is equal to the applied bias voltage. For electrically floating plates the current is set to zero, as in the original version of the code. The potential is calculated on all open field lines in the scrape-off layer, including the private flux region under the x-point. The potential on closed field lines will be considered later.

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Cross-Field Drifts and Periodic Boundary Conditions in the B2 Edge-Plasma Code *

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The two-dimensional fluid code B2[1] is used extensively to model the edge-plasma regions of tokamaks. To date, it ignores the cross-field plasma drifts associated with the vector cross product of gradients in temperature and electrostatic potential with the static magnetic field vector. These drift terms may play an important role in the asymmetry of power to the inner and outer divertor plates and in the L to H mode transition. Inclusion of such terms results in mixed derivatives in the transport equations. These new terms change the difference-equation stensil from coupling five grid points to coupling nine grid points. We have modified the difference algorithms in B2 to account for these mixed derivative terms. At present, we are adding the cross-field drifts using the potential obtained from solving the electron momentum equation along the field line as described in the paper by Rensink, *et al.* at this meeting. The solution for the potential should include the corrections from the cross-field currents which will be added later. The status of our progress with this upgrade will be presented.

We have also implemented changes to B2 which allow one to specify periodic boundary conditions in the poloidal direction for the core-region plasma and for the private-flux-region plasma. Here we treat the boundary conditions in an explicit manner (*i.e.*, using boundary values at the last time-step) in order to preserve the five or nine point matrix operator. Initial tests show that the convergence to steady state is not significantly effected by this departure from a fully implicit scheme.

Finally, we will discuss the development of an analytic framework which can model edge-plasma physics, including possible bifurcations. This will be used to help understand results from the upgraded B2 code.

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Complete Fluid Equations for Singular MHD Modes in Toroidal Plasmas

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A system of equations governing the singular region of MHD modes in toroidal plasmas in the fluid regime has been derived. The equations describe the behavior of the modes in the vicinity of a singular surface for low-m tearing and resistive interchange modes, or in the long tail of high-m resistive ballooning modes.

The equations have been obtained from two equivalent derivations. The first derivation is based on a formal small parameter expansion of the Fokker-Planck equation in which the mean free path is shorter than the macroscopic scale length and the singular layer thickness scales as the geometric mean between the macroscopic scale length and the ion gyration radius. The second derivation is based on an expansion of the Braginskii equations. Among the physical effects included in the equations are the complete viscosity tensor, anisotropic thermal conductivity, anisotropic resistivity, and thermoelectric terms.

An interesting feature of the equations is that, while variation along the field line on a singular surface is determined at lowest order for all quantities *except temperature*, the parallel variation of temperature is more complicated.

The final equations constitute a fourth-order system of ordinary differential equations in which the independent variable is the Fourier transform of the distance across the singular surface, or equivalently the extended distance along the field line in the ballooning representation. Boundary conditions couple the singular region to a global, zero-frequency ideal MHD region. These equations are suitable for efficient numerical solution.

Microstability of Hot Electrons Generated by Intense Microwave Pulses in the Microwave Tokamak Experiment*

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In the Microwave Tokamak Experiment (MTX) at LLNL, high-power microwave pulses from a free-electron laser are injected into a tokamak for heating and current drive. These microwave pulses have peak power of $\sim 1\,\text{GW}$ at the initial frequency of 140 GHz. The intense electric field of $\sim 100\,\text{kV/cm}$ causes a transient, but large, distortion of the electron distribution. In particular, orbit calculations of electrons show a loss-cone type distribution with an extended tail.[1]

We have begun a study of the microstability of such hot-electron distributions using a recently developed code that is capable of solving the fully relativistic dispersion relation for a uniform plasma with an arbitrary distribution function. The distribution function is given numerically on a velocity or momentum grid as an output from the orbit code. For a preliminary study we choose a distribution generated by applying 2 GW of microwave power in a beam with a cross section of 6 cm $\times$ 8 cm into an MTX plasma with a toroidal field of 5 T and a density of $1.8 \times 10^{14}\,\text{cm}^{-3}$. Preliminary results indicate that the whistler mode is unstable for wavenumbers in the range of $ck_{\parallel}/\omega_{ce} \approx 1.5$–3. We present our studies of the whistler, upper-hybrid loss-cone, and cyclotron maser instabilities.

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Development of Godunov Methods for MHD Flows with Shocks*

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The Godunov method[1] and its higher-order extensions[2] have been very successful in treating flows with shock waves in gas dynamics. These algorithms for the inviscid Euler equations are based on exact local solutions to the Riemann problem.[3] They have the desirable properties of being able to describe shock waves and contact discontinuities with a width of only a few mesh points, while preserving monotonicity in the physical variables (i.e., they are non-oscillatory). We are currently extending these Godunov methods to the MHD equations, in order to simulate plasmas with small viscosity and resistivity. In the case of the transverse MHD model (a 2D system in which all quantities vary in the $x-y$ plane, with a magnetic field transverse to the flow, i.e., $\mathbf{B} = B_z(x,y)\hat{\mathbf{z}}$, with flow velocity $\mathbf{v} = v_x(x,y)\hat{\mathbf{x}} + v_y(x,y)\hat{\mathbf{y}}$), the Riemann problem can be solved exactly. We have developed a magnetic Riemann solver which we intend to employ in a 2D transverse MHD code. The 2D code will be based on unstructured adaptive meshes, and will be used to simulate pinch implosions. We will present results from the Godunov treatment of the evolution of shock waves generated during an implosion of a slab pinch, using a 1D code. In particular, we will describe how the vacuum region which arises during the implosion is treated.

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Sherwood Meeting, April 23-25, 1990

Williamsburg, Virginia

Plasma Turbulence Calculations on the Intel RX Hypercube*

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An approach to improve the real time efficiency of plasma turbulence calculations is to use a parallel algorithm that we tested on the 64 node Intel iPSC hypercube. The algorithm was modified to allocate a radial region in each node. In this way convolutions at a fixed radius are performed in parallel and communication is limited to the boundary values for each radial region. The effective memory configuration is a ring. It was shown that it is possible to use 16 modes to achieve a speed-up factor of 4 to 5 [1]. However, with the iPSC it was possible to perform example calculations, but no production computations. Work has now started with the Intel RX which offers clear possibilities as a production machine. Present results, before any optimization of the code has been done, show that the number of steps for CPU time is 30% better for the RX machine using 32 processors than for a single processor CRAY II (for 300 modes and 129 radial grid points). Since 128 processors are available and there is still much optimization work to be done, the RX machine offers a real alternative for carrying out this type of calculation.

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Current Drive via Helicity Waves in Arbitrary Geometry

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Waves with intrinsic helicity can act as an effective medium for the transmission of helicity and the production of currents in plasmas.[1-4] One major limitation of past studies of helicity wave current drive is that they focus on simple, infinite geometries. In this paper, we explore important new issues of helicity wave current drive that are connected with arbitrary geometry. Our preliminary results suggest that plasma inhomogeneities play a key role in the driving of current by helicity waves. Plasma geometry influences the wave propagation and determines the profile of the driven current density. In the present work, we examine the temporal evolution of currents driven by a packet of arbitrarily polarized nonlinear Alfvén waves in an incompressible, weakly inhomogeneous plasma. A wave packet is a natural and convenient analytic wave representation in weakly inhomogeneous media. A packet of circularly polarized waves possesses linkage of wave magnetic field lines due to its localization. A self-consistent analysis of the magnetohydrodynamic equations is carried out using a perturbation expansion about the nonlinear Alfvén wave. Our analysis includes arbitrary equilibrium magnetic field nonuniformity and curvature, mass flow, and density gradients. We find that the plasma inhomogeneities cause a direct transfer of helicity from the applied Alfvén wave to the equilibrium magnetic field. The helicity transfer may be viewed as the conversion of linkage of wave magnetic field lines into linkage of the equilibrium magnetic field lines. The helicity transfer is caused by the dynamo effect and is connected to the shearing of the Alfvén wave phase. At lowest order in the expansion, a nonlinear system of equations governs the equilibrium magnetic field, fluid velocity, density, and pressure. This system of equations reduces to the Grad-Shafranov equation under conditions of axisymmetric toroidal geometry for zero equilibrium fluid velocity. Currents driven by the wave appear at first order in the expansion. Surprisingly, the system of equations at first order may be cast into a linear system, which is solvable if the equilibrium is specified. When the equilibrium magnetic field lines ergodically span a toroidal surface, it is not possible to satisfy boundary conditions with a single propagating wave mode if the frequency of the mode is a constant. Continuity of the wave field requires multiple wave modes, which suggest the existence of standing waves. We are led to examine the most fundamental case of the interaction of two wave nodes. An analysis of the interaction of two waves with differing wave vectors is carried out via a self-consistent expansion scheme. Issues concerning self-consistency of the solutions are addressed together with limitations of the analysis.

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SHERWOOD THEORY THEORY MEETING (April 23-25)

KINETIC ELECTRON MODELLING OF PLASMA NEAR THE NEUTRALIZER PLATE IN A TOKAMAK DIVERTOR

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An electron kinetic code[1] (FPI) is used to simulate longitudinal transport and recycling near the neutralizer plate in a divertor plasma. In addition to the previous features[2], such as Fokker-Planck e-e and e-i Coulomb collisions, transport, ion motion, and a self-consistent electric field, the code now accounts for ionization, excitation, and recycling of hydrogen near the plate. Ions and neutrals are treated as fluids. As one might expect, this full FPI code is very expensive to run, having fast (electron) and slow (ion motion) timescales. We therefore use this FPI code in conjunction with a two-fluid ambipolar code, whose electron heat flow is obtained from usual flux limited coefficients on thermal transport. We alternate the two codes, using the FPI code to correct the fluid code's temperature and local heat transport, while using the fluid code for ion dynamics. We thus arrive at an equilibrium completely consistent with electron kinetics but at a tiny fraction of the cost of doing so with the FPI code alone. Results and applications will be discussed.

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Computer Simulation of Transport Driven Current in Tokamaks

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The inductively pulsed mode of operation typical of tokamak experiments would be undesirable in a reactor; therefore, an efficient, non-inductive means of sustaining the toroidal current is needed. Experiments by Taylor et al[1] on the CCT tokamak at UCLA generate and maintain a steady state toroidal current in the presence of toroidal and vertical magnetic fields, but without any ohmic heating electric field. This current is observed in plasmas generated in a variety of ways, (filament discharge, ECRH, lower hybrid) and always flows in the direction required for equilibrium, even when the filament primary electron current is injected in the "anti-equilibrium" direction, or when the RF is injected without the sort of antenna structure or phasing which theoretically is required for RF current drive. Such toroidal current does not conform to the standard bootstrap current theory[2,3], which requires, as a constant boundary condition, an independently generated "seed current" at the magnetic axis. Bootstrap and dynamo effects spatially amplify the seed current, but cannot drive current at the magnetic axis. The absence of a seed current in the CCT experiments suggests that some other current drive mechanism is at work. To explore the various mechanisms which affect the toroidal current, we have constructed a 2½ dimensional electromagnetic particle code which can model many of the essential features of a tokamak. Like the CCT experiment, the model shows that a Maxwellian plasma in d.c. toroidal and vertical fields spontaneously generates a large toroidal current. The strength of the current and the bulk motion of the plasma sensitively depend on the aspect ratio, the boundary conditions, and the strength of the vertical field. A variety of simulation diagnostics, including particle trajectories, electrostatic potential profiles, and flux surface plots are compared with experimental results and theoretical models. Simulations show that the self-consistent electrostatic potential plays a vital role in the structure of these toroidal equilibria.

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NON-LOCAL EFFICIENCY IN WAVE DRIVEN TOKAMAKS

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The current response induced by suprathermal Landau and cyclotron absorption, in a tokamak plasma, is shown to be non-local. This effect stems from the coupling between space and velocity diffusions. Up to now, for a given wave spectrum, a local response at the radius r was used to describe the result of the competition between the collisional relaxation and the quasi-linear excitation [1]:

$$J(r) = \eta(r)W(r).$$

J is the current and W the absorbed power. Such a process takes place on a slowing down time τ_s. Then, on an anomalous diffusion time scale τ_d [2], this suprathermal current is transported away through radial diffusion. However because of the intricate coupling between the various kinetic processes this picture is to be revisited and three regimes are to be considered.

$\tau_s \gg \tau_d$ the current carrying electrons are deconfined before they are significantly slowed down by the plasma and a fast global loss term in the kinetic equation may account for this situation [3].

$\tau_s \ll \tau_d$ the suprathermal electrons are excited and relax nearly on the same drift surface and a local equation is relevant to describe the current response [1].

$\tau_s \approx \tau_d$ the pertinent physical tool to describe the suprathermal current dynamics arising from the competition between radial diffusion and momentum slowing down is a non-local response [4]:

$$J(r) = \int dr' \eta(r,r') W(r').$$

The physical picture underlying this formula is the following: due to the competition between the slowing down and the anomalous diffusion, a fast electron excited by the waves at radius r' will relax and drive a significant current at radius r. With absorbing boundary condition at the plasma edge and constant radial difusion the ratio of the associated current width Γ to the plasma minor radius a scales as: $\Gamma/a \approx \sqrt{\tau_s/20\tau_d}$. The impact of this anomalous broadening on current profile scenarii is considered.

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Coupled *g*-mode/Resistivity Gradient Driven Turbulence in the Edge of the Reversed Field Pinch*

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Turbulence and transport in the edge of the reversed field pinch (RFP) are studied with a resistive fluid model which couples the dynamics and driving sources of resistive *g*-mode turbulence and resistive temperature-gradient-driven turbulence. Because this model includes a driving mechanism which requires unfavorable curvature (*g*-mode), and one which requires parallel equilibrium current (rippling mode), it incorporates the key features of separate models previously studied as edge turbulence paradigms in the stellarator[1] and tokamak[2], respectively. Examination of saturated turbulence in the RFP for each mode (independent of the other) shows comparable fluctuation levels.

The model system couples electrostatic fluctuations of electron density and electron temperature through Ohm's law, continuity, vorticity, and temperature evolution. Convection by the turbulent ($E\times B$) flow nonlinearly couples the latter three equations. Linearly, the perturbed current of the resistive *g*-mode is localized around the mode-rational surface by line bending, and is insensitive to thermal conduction for finite density gradients. The rippling mode is not centered at the mode-rational surface and is very sensitive to thermal conduction in the linear phase. We examine this linear competition in eigenmode structure for the RFP numerically with a WKB code.

A theory for the turbulent saturation of unstable rippling/resistive *g*-modes is presented. A set of renormalized eigenmode equations are derived with anomalous viscosity in Ohm's law, anomalous perpendicular thermal conduction in temperature evolution, and anomalous particle diffusivity in continuity. The saturated state involves competition of viscous and thermal conductive localization. From energy arguments we show that vorticity and temperature evolution are not decoupled. Limits in which the effect of either branch is weak are examined. A heuristic mixing length model is developed to find the overall fluctuation levels for the combined mode.

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SHERWOOD THEORY MEETING 1990

Resistive Tearing Mode Instability With Shear Flow*

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The linear theory of tearing mode instability in slab geometry,[1] was recently extended by introducing the effect of equilibrium shear flow.[2] Here, the method of numerical solution for the time dependent resistive equations[3], is generalized to this problem and growth rate scalings are obtained. The results of the computations are compared to previous work,[4] and the emerged growth rate scaling agree with the analytical predictions. Namely, the "constant-ψ" growth rate scales as $S^{-1/2}$ and the "non-constant-ψ" growth scales as $S^{-1/3}$. The FKR scaling of $S^{-3/5}$ is reproduced for small values of shear flow. The presence of flow introduces a second peak in the flow eigenfunction, which is outside of the peak produced by the solution without flow.

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Burn Threshold for Fusion Plasmas with Helium Accumulation*

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The classic requirements for fusion power generation (e.g., that $n\tau T > 2\times10^{21}$ sec keV m^{-3}, or, equivalently, $\beta B^2\tau > 1.6$ $Tesla^2 sec$) ignore the thermalized helium population, which can dilute the D-T fuel and increase the energy loss due to bremsstrahlung radiation.This helium "ash" accumulation could be of importance in predicting the performance of ignition experiments such as ITER and CIT: both devices appear to lie below the simplified ignition thresholds if they operate in L-mode, so $\beta B^2\tau$ must be increased, for example by operating in H-mode, which increases τ by a factor of two or more. However, the particle confinement time also increases, and by a much larger factor, so the ratio $\gamma \equiv \tau_\alpha/\tau$ of effective α particle containment time to central energy confinement time can increase appreciably during a transition from L-mode to H-mode. Using a simple, phenomenological model, we find that γ is a crucial parameter for both ignition and steady steady burn. Our model assumes that the electron density n is feedback controlled, and hence can be treated as a constant; that the central energy confinement time τ determined by plasma processes other than bremsstrahlung and synchrotron radiation is also a constant; and that all species can be represented by a common temperature T. Conservation of energy and α particles then leads to two coupled differential equations for T and the relative helium ion concentration $\alpha \equiv n_{He}/n$. Analysis of this system shows that the $nT\tau$ required for ignition rises rapidly with increasing γ and no steady state D-T burn is possible for $\gamma > 15$ for an impurity free plasma. For example, if $n\tau$ is kept at 2.5×10^{20} sec m^{-3} and external power of 0.1 $Mw/m^3/(n_{20})^2$ is supplied until T reaches 20 keV, the plasma will ignite and burn only if $\gamma < 5$. For larger γ there is only transient ignition. Inclusion of the effects of small amounts of impurities, such as Be, significantly lowers the permissible values of γ: We conclude that to achieve sustained ignition it will be essential to increase τ and, at the same time, keep γ as low as possible, i.e. limit τ_α.

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Wave-kinetic Formulation of Incoherent Linear Mode Conversion

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We consider a weakly inhomogeneous plasma which supports at least two distinct wave modes with dispersion function $D_a(\mathbf{x},t,\mathbf{k},\omega)$ and $D_b(\mathbf{x},t,\mathbf{k},\omega)$. In certain localized regions of the wave phase space $(\mathbf{x},t,\mathbf{k},\omega)$, both dispersion functions can simultaneously vanish, leading to linear mode conversion (e.g. as occurs for Bernstein and magnetosonic waves in tokamaks). Matching conditions which relate the incoming and outgoing wave amplitudes (i.e. the S-matrix) can be derived by metaplectic techniques[1]. If the incoming waves are incoherent, then, although the mode conversion conserves energy, momentum, and action, it acts as a source of wave entropy[2]. Thus the process is irreversible even when the original wave equations are nondissipative. Incoherent mode conversion drives the system toward equal action densities of the two modes, i.e., equipartition.

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THE $m = 1$ INTERNAL KINK MODE IN A ROTATING TOKAMAK PLASMA WITH ANISOTROPIC PRESSURE

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An ideal MHD stability analysis of the internal $m = 1$ mode in a toroidally axisymmetric plasma has been performed analytically, using an expansion to powers of the inverse aspect ratio of the torus. The purpose of the present work is to describe the fast crash phase of sawtooth disruptions. Since neutral beam injection in tokamaks can cause plasma rotation frequencies that are comparable with the sawtooth collapse time, the $m = 1$ stability of stationary rotating equilibria with toroidal and poloidal velocity components is considered.

The equilibrium pressure may be anisotropic due to poloidal plasma rotation, or due to some additional heating method. Instead of assuming a fluid equation of state, the parallel kinetics of the particles are treated to leading order in the guiding centre approximation.

The ordering of equilibrium quantities is such that the method of Reference [1], which has been proven to be very useful in the case of a static plasma with isotropic pressure, can be applied without important modifications. This method treats the $q \approx 1$ region of the plasma in a special way in order to accurately describe the cases with the highest growth rates.

The derived dispersion relation is an implicit equation for the growth rate as a function of the equilibrium velocity, the current profile, and the parallel and perpendicular pressure components. Parallel variations of the pressure components are expressed in terms of moments of the guiding centre distribution function. These moments are non-equilibrium generalizations of the integrals $C_r^{\pm}$ of Reference [2].

The effects of plasma rotation and pressure anisotropy on the $m = 1$ stability will be presented.

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HIGH-DENSITY Z-PINCHES FROM A COMPUTATIONAL VIEWPOINT

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Experiments at Los Alamos (and elsewhere) have shown that interesting fusion plasmas having densities many orders of magnitude higher than conventional MFE experiments can be created in relatively simple linear Z-pinch geometries. A plasma density of $10^{20}/cm^3$ at a temperature of 200 eV was attained in a Los Alamos laser-initiated, gas-embedded Z-pinch[1]. More recently, a plasma with a density of 2 x $10^{21}/cm^3$ and temperature of 400 eV was created in the Los Alamos cryogenic solid deuterium fiber Z-pinch [2].

The high-density Z-pinches are amenable to computer modeling in the magneto-hydrodynamic (MHD) limit. Our two-dimensional computations of the laser-initiated z-pinch reproduced all experimental observations (current initiation time, Schlieren shadowgraphy, visible emission, and X-ray emission) to a remarkable degree[3]. Our computations of fiber-formed Z-pinches are suggesting $m=0$ behavior in a hot, exterior coronal plasma prior to complete ablation of the cold fiber [4]. Our computational model includes resistive diffusion, electron and neutral resistivity, electron and ion thermal conduction, line and continuum radiation, a realistic non-ideal-gas equation of state, and "cold-start" initial conditions in an attempt to compute the behavior of the pinches from $t=0$.

The computations of the laser-initiated Z-pinch were required to resolve conflicting interpretations of the experimental measurements. The computations of fiber-formed pinches contradict an interpretation of the abrupt expansion of the visible light emitting region as an indication of the onset of instability [5], suggesting instead that the rapid expansion concides with complete fiber ablation.

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Curvature Drift Modifications of Magnetic Field Maps for Runaway Electrons in the TEXT EML Configuration*

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Ergodic magnetic limiter (EML) coils on TEXT are used to create an edge layer in which the perturbing magnetic field forms either coherent islands, a stochastic region, or a mixture of both.[1] The eight, toroidally localized EML coils enhance the thermal electron diffusivity[1] and, at the lower coil currents, increase the thermal particle transport.[2] Runaway electrons are created in TEXT to probe the edge region in an attempt to gain further insight into the mechanisms responsible for these changes.[3] By adopting and generalizing the composite map techniques employed by Martin and Taylor,[4] the curvature drift of the runaways is retained. Various phase space preserving maps are being investigated to determine curvature drift effects on runaway electron losses in TEXT during EML coil operation. The ultimate goal is to determine whether the retention of curvature drift ever makes EML coil induced runaway losses smaller[5,6] than the driftless predictions.

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"Universal" Nonlinear Drift-wave Turbulence

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Turbulent, collisional drift-wave dynamics are studied numerically in a 2D sheared slab. All relevant electron temperature effects, including the resistivity perturbation ("rippling"), as well as coupling to parallel ion flow, are retained. Although the background temperature and density gradients are maintained, no external drive of any sort is employed. As is well known, the linear waves are stable in the sheared slab, unless destabilised by rippling. Nevertheless, the nonlinear turbulence takes on a changed mode structure so as to allow a vigorous saturated state, if the amplitude is initialised nonlinear. The saturated amplitudes for density and temperature are several times ρ_s/L_T, approaching the so-called mixing level. The energy balance is struck between the temperature gradient as the source, and the twin sinks represented by collisional current dissipation and thermal conduction. The fluctuations are nonlinearly self-localised by recycling energy transferred to ion velocity at large scales back into electrostatic potential at small scales, with the result that little energy is lost to parallel viscosity (the ion Landau damping model). All of this is underpinned by the cascade dynamics of the various fluctuations. The temperature gradient is a sufficiently powerful source that the turbulence does not react strongly to the relative phases produced by the nonadiabatic density dynamics. As a result, coherent structure in the density plays no role for moderate to large L_n/L_T, and the time-averaged density gradient free-energy feed is small. The resistivity perturbation has no effect on the saturated state below its linear threshold. These results, occurring as they do in so generic a sheared system, are consistent with the ubiquitous observation of tokamak edge fluctuation levels sharply increased over the interior in the case that the plasma edge is collisional.

Particle Dynamics in the Neighborhood of a Magnetic Null

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In a collisionless plasma, test-particle modelling can lend some insight into the behavior of the plasma as a whole. We are currently studying the properties of charged particle motion in the vicinity of a magnetic null. Null points are of interest in the study of magnetic reconnection,[1, 2] and in particular, the investigation of processes in the nightside of the Earth's magnetosphere. Near a null point, the magnetic field may be written as[3]

$$\mathbf{B} = \mathbf{M}\,\mathbf{r},$$

where $\mathbf{M}$ is a 3 x 3 matrix of constants and $\mathbf{r} = (x, y, z)^t$, with the null point (or line) located at (running through) the origin. One example of such a situation that has received attention recently is Martin's model of the particle dynamics near an X-type magnetic neutral line subject to a uniform electric field[4]

$$\mathbf{B} = z\hat{\mathbf{i}} + \delta x\hat{\mathbf{k}}, \quad \mathbf{E} = E\hat{\mathbf{j}},$$

where δ is a constant parameter. Integration of the equations of motion for a large ensemble of test-particles and comparison of the current predicted by Ampère's law with the y-component of the velocity leads to a relationship between current and applied electric field that is linear, given a sufficiently large value of E, allowing one to define an effective conductivity[4]. Painlevé analysis[5] of the equations of motion of this system implies that for suitable choices of the parameter δ, the test-particle equations of motion may be integrable, which might have some observable effect on the conductivity. A numerical investigation of this effect using Poincaré surface-of-section plots is currently in progress.

A discussion of applying the symbolic manipulator Mathematica to implement the Painlevé property test for these models, as well as numerical results will be presented.

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SHERWOOD THEORY MEETING 1990

Exact Nonlinear Solutions for Drift-RMHD Dynamics*

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Presented is a method of constructing exact solutions for a system of nonlinear plasma fluid equations. This system[1] combines the physics of reduced MHD[2,3] and the electrostatic drift-wave description of the Hasegawa-Mima equation.[4] First some motivation and a physical interpretation of the solutions are provided;[5] then the method and its results are summarized. A distinguishing feature is that the original nonlinear problem is reduced to the solution of systems of *linear* partial differential equations with Hamiltonian characteristics. The method relies on modifying a class of simple equilibrium solutions; no approximations are made. Explicit solutions are constructed for some special cases and their physical meaning is examined. Finally, some areas for further work are suggested.

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ITERATIVE SEMI-IMPLICIT SCHEME

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Semi-implicit computational schemes avoid the time step restrictions imposed by the fastest modes encountered in MHD systems by using a semi-implicit operator. However, this operator is complicated for toroidal systems, precluding a satisfactory solution for the long time scale MHD behavior of tokamak-like plasma systems. The key difficulty arises from the need to use unsatisfactory matrix inversion schemes for the implicit part of the problem. However, the iterative solution using the semi-implicit operator is found to possess the same convergence properties as the implicit step of the semi-implicit scheme. This fact is demonstrated theoretically and computationally in slab geometry. The virtue of employing this scheme in complicated geometries will also be discussed.

ELECTRON CYCLOTRON HEATING STUDIES IN THE COMPACT IGNITION TOKAMAK*

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The possibility of electron cyclotron heating (ECH) in CIT is being studied by a combined code in which electron cyclotron radio-frequency (ECRF) ray tracing and absorption, an MHD equilibrium calculation, and thermal and particle transport are treated self-consistently. The ECRF package is a variation of the TORAY code [1], valid in the Doppler and relativistic regimes. Previous studies [2] of electron cyclotron resonance heating (ECRH) in CIT were carried out using model profiles of ECRF absorption based on stand-alone ray tracing calculations. Transport calculations of equilibrium and flux surface averaged quantities are carried out using a modified version of the Baldur 1 1/2 D code [3]. Expressions for the electron and ion thermal diffusivities have been benchmarked against the results of high power neutral beam injection experiments in TFTR [4]. The calibrated code has been used to simulate ECH assisted start-up and heating for CIT. Results will be presented for ECH assisted start up where the toroidal field is ramped from $B_T = 7.5\text{T}$ to 11T, while the density and temperature are increased from $n_e(0) \simeq 2 \times 10^{20}\text{m}^{-3}, T_e(0) \simeq T_i(0) \simeq 5$ keV (ohmic phase) to $n_e(0) \simeq 8 \times 10^{20}\text{m}^{-3}, T_e(0) \simeq T_i(0) \simeq 25$ keV (burn phase). The ECRF is assumed to be at a fixed frequency of f = 308 GHz and is launched in the ordinary (0-mode) of polarization from the low field side of the tokamak. The incident EC wave propagation angle is adjusted to maintain efficient plasma heating [1,2]. In the future, this code will be used to optimize ECRH in CIT by including various transport models.

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Numerical Study of the Spectrum for Nonneutral Plasma Equilibria

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An eigenvalue code using finite elements has been developed for exploring the spectrum of linear modes for a nonneutral plasma confined in cylindrical geometry. Presently, inertial effects are included but only for infinite-length equilibria. Comparisons with results for standard density profiles and results from a shooting code will be given.

Hamiltonian Chaos and Anomalous Transport

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A new concept of anomalous diffusion of particles is introduced. It is based on the micro-properties of a phase space of Hamiltonian chaos which provides the trappings and flights. In general, full process of transport can be considered as a generalization of Lévy random walk to a multifractal situation. This leads to the appearance of very long and very fast jets of orbits which are responsible for the many anomalous properties of the transport.

Several numerical simulations are given to illustrate this phenomena. They are concerned with the particle motion in a constant magnetic field and a wave packet, the particle motion in 2D quasiperiodical potential, and the passive particle motion in a quasiperiodical 3D steady flow.

Multifractal random walk theory is proposed.

Simulation of a 2-D Model of Dissipative Convective Cell Turbulence

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A 2-D turbulence simulation based on a model by Kodomtsev and Pogutse is used to study dissipative convective cell turbulence. This model incorporates the local dynamics of collisional trapped ions in a one field model of relevance to core fluctuations and transport in tokamaks. Simulations are performed using a spectral code which is run with a relatively small number of k space modes (up to 11×11). The model conserves internal energy when dissipation (damping and driving) is suppressed. As a check of the numerics energy is observed to be rigorously conserved in this case over a period of many ($>10^3$) eddy turnover times.

A key feature of dissipative convective cell turbulence is a direct cascade of energy from the large wavelengths associated with trapped ion motion to small scales where it can be dissipated by mechanisms not incorporated in the basic model. This cascade is inferred from the existence of a single quadratic invariant and from the sign of the nonlinear transfer terms in the renormalized equations. The existence of a direct cascade of energy contrasts with other more familiar models of 2-D plasma turbulence in which two quadratic quantities are invariant. The existence of the direct cascade is verified in simulation by comparison of wave number spectra with the predictions of equilibrium statistical mechanics for the dissipationless case. The results indicate a transfer of energy to high k_y consistent with closure theory. As a direct measure of the energy flow in wavenumber space, nonlinear transfer rates across lines in k space are computed in the simulations.

Driven/damped turbulence is also studied in order to verify mixing length saturation level estimates and determine transport properties. Nonlinear decorrelation times and frequency spectra are also examined, specifically in the context of weak versus strong turbulence regimes.

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Analysis of Alpha Physics Aspects of the IGNITEX Experiment*

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The IGNITEX experiment proposed by Rosenbluth, Weldon, and Woodson on the basis of Coppi's ideas for a thermonuclear experiment is analyzed. Ignition conditions are accessible by ohmic heating alone. Alpha heating is shown to be rather efficient because of the small alpha Larmor radius and the high plasma current. The characteristics of the IGNITEX experiment for alpha kinetics and containment are discussed. Thermally stable ignited plasmas can be produced in the IGNITEX device. Thermal damping is possible because of electron cyclotron emission at low plasma beta. Alpha stability of fishbones, ballooning, and TAE modes is analyzed It is shown that the IGNITEX experiment could approach ignition conditions with minimum destabilization of ideal MHD modes. Ignition is also accessible through regimes in which these modes are predicted to be unstable. Characteristic plasma time and length scales through a typical discharge are examined.

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Theory of the Tokamak $\beta aB/I$ Limit

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A theoretical framework is developed which leads to a first principle demonstration of the Troyon form of the beta limit $\beta aB/I < C_T$, and shows its dependence on the safety factor. The fundamental idea is to carry out the beta optimization at constant but arbitrary q_o, and then investigate the dependence of the coefficient C_T on q_o. For configurations with smooth pressure and current density profiles that vanish at the plasma edge, there exists a non-trivial scaling that transforms $\beta_p \rightarrow \beta_p$, $\beta \rightarrow \lambda^2\beta$, $q \rightarrow q/\lambda$, and leaves the tokamak equilibrium equation invariant in the limit of large q (both q_o and q_a). It is shown that, in such asymptotic regime, the ideal MHD stability equations also become invariant under that scaling and independent of the toroidal mode number. Therefore the relevant stability limits should be expressed in terms of invariant parameters only. For a given geometry of the plasma cross section, there is only one such global parameter that remains bounded in the event that a separatrix approaches the plasma boundary, and reflects the fact that the beta limit against pressure driven modes results from a competition between the pressure gradient and the magnetic shear. This only natural stability parameter is $\epsilon\beta_p q_o/q_{cyl}$ or equivalently $q_o\beta aB/I$. The conclusion is that the Troyon form of the beta limit must be generalized to $\beta aB/I < C_R(q_o)/q_o$, $C_R(q_o)$ being a weak function of q_o that becomes constant in the limit of large q_o. Moreover, the asymptotic value $C_R(q_o \rightarrow \infty)$ is independent of the toroidal mode number. Numerical results that confirm all these theoretical predictions are presented.

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Calculation of 3-D equilibria with islands for the IMS Stellarator *

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Experimental results for the IMS stellarator show constant pressure contours [1] and Electric field potentials which are consistent with the presence of large magnetic islands. These equilibria are also characterized by hollow density profiles.

We use the BETAS code [2], which allows for non-nested magnetic surfaces, to compute equilibria for the IMS configuration. In order to better understand the experimental results, we compare solutions obtained by minimization of the potential energy with respect to topology variation (i. e. island size) with those observed in the experiment.

These computed 3-D equilibria can be the basis for a future Monte-Carlo study of the effects of islands on particle transport in stellarators.

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Numerical Model of Multifield Plasma Turbulence Based on DIA Closure*

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We have developed a general anisotropic DIA code which treats an arbitrary number of dynamical fields coupled through linear and quadratic interaction in a periodic domain of arbitrary dimension. This work is designed in part to determine the range of applicability of analytic simplifications of the full DIA formalism for multifield plasma models. We give preliminary results of the first applications of the code to model the Hasegawa and Wakatani[5] two-field model of drift wave turbulence.

Code numerics are based in part on fast transform methods for evaluation of spectral convolutions defining the renormalized self-energies. With this design, the leading operations count for the spatial portion of the computation scales with problem size in the same fashion as that for direct simulation. The number of convolutions has been minimized by creation of a mask based on the structure of nonlinear interactions present in the primitive equations. Time advance of the non-Markovian evolution equations is carried out with a predictor-corrector method using a simple closed quadrature rule for the time-history integrals. The code design preserves identically those conservation properties present in the continuous DIA closure equations.

Each application for this code is created through definition of the interaction coefficients present in the primitive equations, and specification of initial equal-time covariance spectra for all field combinations. The code then computes the time-evolution of all two-point, two-time second moments and renormalized response functions for the system. From these quantities, anisotropic spectra of single-time quantities such as mean turbulent intensities and fluxes may be computed, as well as time correlations and nonlinear response functions.

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STABILIZATION OF DRIFT-TEARING MODES AND BREAKING CONSTANT-Ψ

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A region of stability, in $\omega_{*e}\tau_H - \Delta'$ parameter space (where $\omega_{*e} = (mc/eBrn)(dp_e/dr)$ = electron diamagnetic frequency, m = poloidal mode number, τ_H = characteristic hydrodynamic time, Δ'=stability parameter for tearing modes) is discussed [1]. The growth rate of the drift-tearing mode is found to be a non-monotonic function of Δ'. As Δ' increases from zero, it first reaches a maximum for $\Delta' \approx 0.5\Delta_1'$ and becomes negative for $\Delta' \geq \Delta_1' \approx 2m/\sqrt{\tau_H\omega_{*e}(\omega_{*e}-\omega_{*i})}$. As this threshold for re-stabilization is approached, the mode eigenfrequency, ω moves further and further away from ω_{*e}, and the mode eigenfunction acquires a strongly varying form within the singular layer. This is recognized as the breakdown of the constant-Ψ approximation, which occurs [2] in conjunction with large parallel electron currents within the layer, shielding of the perturbation from the ideal region and inhibiting reconnection.

As Δ' is increased further past a second threshold value $\Delta_2' \approx \sqrt{2\tau_H\omega_{*e}/\epsilon_\eta}$ (where ϵ_η is a measure of the collisional resistivity), a second root becomes unstable. This root corresponds to the diamagnetic modification of the $\epsilon_\eta^{1/3}$ version of the resistive tearing mode. For the $m = 1$ case this mode is known as the resistive internal kink. It stabilization for $\Delta' \leq \Delta_2'$ is understood to arise from the lessening in the free energy available to the mode from the plasma pressure gradient.

This window of stability had been identified previously [3]-[4], but its large width had been hitherto unrecognized. Its primary dependence is on ω_{*e}, with a weak dependence on the electron-ion temperature ratio: it disappears entirely for $\omega_{*e}\tau_H \leq 0.83\epsilon_\eta^{1/3}$. This theory applies directly to resistive $m = 1$ modes with the substitution $\Delta' \to -m\pi/\lambda_H$.

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A Boundary Integral Method for Computing Minimum Energy States *

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This poster will describe a boundary integral method for computing solutions to the force-free equation $\vec{j} = \lambda\vec{B}$ with constant λ. The advantage of this method is that it only requires a mesh on the boundary, not in the volume, hence it is very fast and can easily accommodate any arbitrary boundary shape. A code has been written implementing this method for axisymmetric boundaries of arbitrary cross section, and can find solutions with any toroidal mode number. Convergence and timing properties of the code will be discussed and sample calculations presented.

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RESISTIVE MODES IN TOKAMAKS

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Abstract

A normal mode analysis for general dissipative perturbations of tokamak equilibria is performed exploiting straight field line flux coordinates. The linearised equations of motion of resistive MHD, involving the state vector $\mathbf{w} \equiv (\rho_1, \mathbf{v}_1, T_1, \mathbf{B}_1)$, are written as

$$\mathbf{S}\,\frac{\partial \mathbf{w}}{\partial t} = \mathbf{R}\,\mathbf{w}\,, \tag{1}$$

when $\mathbf{S}$ and $\mathbf{R}$ are matrix operators depending on the equilibrium quantities, the metric, and the differential operators in the poloidal plane. Introducing normal modes $e^{\lambda t}\,\mathbf{w}(\mathbf{r})$ and applying the Galerkin method in conjunction with finite elements leads to the generalised non-symmetric eigenvalue problem

$$\mathbf{A}\,\mathbf{x} = \lambda\,\mathbf{B}\,\mathbf{x}\,, \tag{2}$$

where $\mathbf{A}$ and $\mathbf{B}$ are block tridiagonal matrices. This problem is solved accurately and efficiently by inverse vector iteration, Lanczos, and QR procedures. This method is embodied in the numerical program CASTOR which computes the complex Alfvén spectrum for toroidal plasmas.

The resistive Alfvén spectrum is computed for a toroidal elongated tokamak plasma exhibiting the influence of resistivity on the discrete and continuum modes. The global Alfvén eigenmodes in the gaps of the ideal continua, which are of great interest for heating, are studied.

Applications to resistive instabilities of JET plasmas will be presented.

FRC Vlasov-Fluid Global Stability Calculations Using MHD Eigenfunctions as Basis Functions*

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The stability of large-scale MHD-like modes can be substantially altered by the presence of large thermal ion orbits in experimental FRC plasmas. The Vlasov-fluid model (Vlasov ions, massless fluid electrons) keeps nonlocal effects due to large ion orbits, parallel ion motion along magnetic field lines, the Hall term, and resonant particle effects which are neglected in the MHD model. A Vlasov-fluid dispersion functional is used to calculate eigenfrequencies and eigenfunctions using unstable MHD eigenfunctions as basis functions. Use of these basis functions has expanded the range of FRC equilibria and modes that can be studied beyond what was allowed by the restrictive rigid-axial-shift basis functions previously used to study the FRC tilt mode. Results will be presented showing the effect of equilibrium profile variation on the stability of the FRC tilt and mushroom modes. One interesting result is that the Vlasov-fluid growth rate of the tilt mode in FRC's with small elongation in the small gyroradius limit lies well below the MHD growth rate. This presumably is due to a large parallel viscosity effect due to the motion of ions along magnetic field lines.

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Recent Results in Numerical Modeling of the RACE Experiment*

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The recently developed two-dimensional, Lagrangian, magnetohydrodynamic code, TRAC, has been applied to modeling of the RACE experiment at LLNL. RACE has demonstrated acceleration of compact toroid plasma rings to velocities of several hundred centimeters per microsecond after formation in a magnetized coaxial plasma gun. The accelerated plasma rings have been subsequently precompressed and focused in various converging conical electrode configurations. Modeling of these experiments has motivated the development of the magnetohydrodynamic TRAC (Two-Dimensional RAC) code which allows the use of arbitrarily configured, axisymmetric electrode boundaries, and non-rectangular computational grids. A self-consistent treatment of an external capacitor bank circuit provides the accelerating toroidal field. The initial (axisymmetric) ring magnetic field configuration can optionally be initialized to a Taylor state equilibrium by iterative relaxation to the lowest-energy eigenfunction for fixed helicity. For analysis of tilt-mode stability in a specific electrode geometry, the user may also request iterative solutions to the lowest energy eigenfunctions for toroidal mode number $m > 0$. Representative results of the numerical simulation for ring precompression, acceleration, and focusing will be presented and compared with available experimental data.

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3-D MHD with Two-Fluid Corrections for the Reversed Field Pinches *

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Previous work[1] was shown that nonlinear two-fluid effects require finite β and results depend strongly on the viscosity. Consequently, one must accurately include self-consistent anisotropic thermal conduction as well as the viscous stress tensor to correctly model two-fluid effects. We are incorporating both of these effects using the Braginskii[2] forms. Since these forms are anisotropic, they introduce new nonlinearities into the system. We have developed new semi-implicit operators to handle these terms. Preliminary results will be presented.

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MULTIFRACTAL PROPERTIES OF PASSIVE SCALARS CONVECTED BY CHAOTIC FLUID FLOWS

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The passive convection of scalar functions by a prescribed incompressible fluid flow $\mathbf{v}(\mathbf{x}, t)$ is considered for the case where $\mathbf{v}(\mathbf{x}, t)$ is chaotic. By chaotic $\mathbf{v}(\mathbf{x}, t)$ it is meant that typical nearby fluid elements diverge from each other exponentially in time. It is shown that in such cases, as time increases, the gradient of a convected scalar will generally concentrate on a set which is fractal. The present paper relates the stretching properties of the flow to the resulting fractal dimension spectrum of the magnitude of gradient of the scalar as well as to the wavenumber dependence of the power spectrum of the correllation function. Fundamentally different results apply for the small diffusivity limit of the "initial value problem" (in which an initial passive scalar density evolves in time with no passive scalar source present) and the "steady state problem" (in which a statistically steady passive scalar source is present and one seeks time-asymptotic steady properties). For the initial value problem the spatial power spectrum is related to the fractal dimension spectrum and to the distribution of stretching rates (finite-time Lyapunov exponents) of the flow. For the steady state problem, it is shown that the initial value results may be utilized to obtain the known k^{-1} power spectrum ("Batchelor's law") in a clear and edifying manner. These ideas will be illustrated with simple numerical examples. Finally, motivation for these considerations is provided by recent experiments which demonstrate the possibility of measuring the fractal dimension of the gradient squared of convected passive scalars.

An Approach to Time Series Data Analysis of Dissipative Driven Tokamaks

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The theory and application of time series data analysis of tokamak data is presented. In particular, we focus on extracting coherent features of beam driven tokamak discharges such as those of TFTR. It is assumed that the data is obtained by a non-obtrusive method such as that from soft x-rays or electron cyclotron emission.

Because the discharges are driven and dissipative, the plasma is non-linear and is therefore not, in general, entirely amenable to standard Fourier methods, although such methods may be used for specific cases. One such case is for discharges where particular modal structure and toroidal rotation is evident. In this situation the power spectral density exhibits a dominant peak at the rotation frequency. In the case where single modal structure can be inferred, tomographic profiles can be reproduced from direct Fourier analysis. These methods are similar to those used in the imaging of moving objects using synthetic aperature radar (SAR)[1]. However, in the absence of rotation and/or Fourier modal inference, coherent features may still be extracted using principal component decomposition[2]. This method makes use of the natural structure of the data to develop "empirical" eigen-functions. In addition to expressing the information more compactly, these basis function are better adapted to extracting fine features from the data. TFTR soft X-ray data is examined in both cases.

The non-linear features of the time series are further characterized using methods of non-linear dynamics. We express this character in terms of the Grassberger-Procaccia dimension, while the degree of predictability is estimated from analysis of the Liapunov exponents[3] A non-trivial dimension indicates turbulent, nonlinear behavior. The theory is outlined and the applicability to the TFTR is discussed.

This theory and methodology is applied to soft x-ray data obtained from the PPPL MHD data analysis group for neutral beam driven discharges.

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$1\frac{1}{2}$-D Transport and Stability Calculations

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Abstract

A $1\frac{1}{2}$ -D transport code based on large aspect ratio, shaped cross-section Tokamak equations (ellipticity $\sim$ triangularity $\sim 0(\epsilon)$) has been used to evolve equilibria with $q_0 < 1$. The equilibrium part of the calculation extends the global description of Greene, Johnson and Weimer to include shaping effects. Flux surface averages are performed analytically up to $0(\epsilon^3)$ and the resulting 1-D equations form the basis of a, computationally fast, radial transport package. Initial equilibria are chosen to be stable to the m=n=1 ideal and resistive mhd modes. As the equilibria evolve various linear stability criteria are evaluated. These include the toroidal Δ' for n=1 modes, Mercier criterion D_I and resistive interchange criterion D_R. The correlation of experimental sawtooth collapses with violation of these stability criteria is investigated.

Numerical Simulation of Ion Temperature Gradient Driven Modes in the Presence of Ion-Ion collisions

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Ion temperature gradient driven modes in the presence ion-ion collisions in toroidal geometry with trapped ions have been studied by using $1\frac{2}{2}d$ linearized gyrokinetic particle simulation code.[1] The purpose of the investigation is to try understanding the effects of trapped ions on H-mode discharges of DIII-D Tokamak. The results for threshold conditions of L_t/R_0 and an upper bound on k_y, linear growth rates and mode frequencies of collisionless ion temperature gradient driven modes are obtained. The transition of ion temperature gradient driven instabilities from slab to toroidal geometry with trapped ions will be demonstrated. A Monte-Carlo scheme for inclusion of ion-ion collisions, in which ions can undergo coulomb collisional dynamical friction, velocity space diffusion and random walk of guiding centers, has been constructed. The effects of ion-ion collisions on the long wave length limit of the ion modes will be discussed.

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THE 1990 INTERNATIONAL SHERWOOD THEORY MEETING

PROPAGATION OF ION-BERNSTEIN WAVES IN TOROIDAL PLASMAS*

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In tokamak plasmas ion-Bernstein waves (IBW) can be excited by mode-conversion of the externally launched fast Alfvén waves during ICRF heating. A detailed numerical and analytical analysis of the propagation of these IBW in toroidal plasmas yields some very interesting features about the propagation characteristics of the IBW [1]. The IBW are found to damp primarily onto the electrons by an upshift in the poloidal mode numbers during propagation. However, the region where this damping takes place is dependent on the ratio of the poloidal magnetic field (or, equivalently, the plasma current) to the toroidal magnetic field. As this ratio decreases the IBW damp onto the electrons closer to the plasma edge. Furthermore, the toroidal excursions of the IBW increase as this ratio decreases. The upshift in the poloidal mode numbers is not unidirectional. The direction of the upshift is determined by the horizontal axis of symmetry of the plasma. Above this axis the upshift is towards larger negative values and below the axis the upshift is towards larger positive values. Consequently, ion-Bernstein waves are not good candidates for driving plasma currents. Complete details of all the results will be presented.

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Spontaneous Poloidal Spin-up of Tokamaks and Enhanced Confinement

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It is shown that a tokamak discharge with particle transport at the anomalous level is prone to a *spontaneous* spin-up of poloidal rotation. This spin-up tendency is the same as the one discovered by Stringer,[1] for Pfirsch-Schluter particle transport. We show that the requirements for the spin-up are (1) that the particle transport be larger outside than inside by an asymmetry factor greater than ϵ, and (2) that, roughly, the local particle transport rate exceed the local rotation damping rate from magnetic pumping, i.e.,

$$D(n'/n)^2 > \gamma_{mp} \tag{1}$$

where D is the particle diffusivity, and ϵ is the inverse aspect ratio. The likelihood that a shear in the poloidal rotation will quell microinstabilities, when taken together with the $(n'/n)^2$ dependence in (1), leads to the possibility of a bifurcation. One equilibrium state is where (1) does not hold anywhere, there is no rotation, and transport is large. A second state can now be accessed by locally increasing n' such that (1) is satisfied, thus initiating rotation, which leads to a smaller D, thus increasing n' even further to maintain the particle flux. Such a bifurcation is shown, by numerical simulation, to exist and to be stable.

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SHERWOOD THEORY MEETING 1990

Finite Bloch-shift effects on drift wave stability in toroidal plasmas

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Effects of a finite Bloch shift in the ballooning wave function on the stability and the localization of drift wave eigenmodes are analyzed for axisymmetric toroidal plasmas with shifted circular magnetic surfaces. We consider a model equation which contains the toroidal coupling due to ion magnetic drifts and the stabilizing effect of shear, but neglects kinetic effects due to trapped electrons. In the small beta limit an analytical dispersion relation is derived for the toroidicity induced eigenmodes, corresponding to the stationary Bloch shifts $\eta_0 = n\pi$, $n = 0,1,2,\ldots$. The analytical results are shown to agree well with those of numerical solutions and indicate that, with trapped electron dynamics, $\eta_0 = 0$ corresponds to the most unstable eigenmode. The case with finite beta effects will also be discussed.

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Reciprocity Relations and the Mode Conversion-Absorption Equation with an Inhomogeneous Source Term

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While considerable work has been done on the effects of mode conversion on absorption in tunneling layers at cyclotron harmonics, the effects of mode conversion on emission have had little attention. Recently, the basic relationship has been found for absorption and emission in mode conversion layers[1]. This relationship is shown to be the same as Kirchhoff's law and has been derived from the law of equipartition of energy and the reciprocity relations. Kirchhoff's law is valid for any source or sink as long as the reciprocity relations hold.

Therefore, it is important to investigate the reciprocity relations more closely, which have been known numerically and have been proved analytically by Imre and Weitzner[2]. But it may not always be justified to consider only the real adjoint of the governing equation as in their proof, and the sufficient condition for reciprocity is not presented.

In this paper, reciprocity relations which lead to Kirchhoff's law are proved in the course of obtaining the Green function of the mode conversion-tunneling equation with an inhomogeneous source or sink term and the sufficient condition for reciprocity is discussed.

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Absorption and Emission of Plasma Waves at High Harmonics of the Ion Cyclotron Frequency

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The mode conversion-tunneling equation is solved numerically with the resonant absorption term at general harmonics of the ion cyclotron frequency. The numerical technique is based on the Laplace contour integral and direct integration. A hybrid technique is developed for the mode conversion-tunneling equation with absorption at general harmonics of the ion cyclotron frequency. A contour integral is used to obtain accurate asymptotic solutions, which are directly integrated across the domain and are then matched with asymptotic solutions on the other side. Results for various scattering parameters as well as absorbed fractions of incident energy are presented for harmonic numbers $n = 2, 3, 4, 5, 6$. As in the second and the third harmonic cases, simple expressions for some scattering parameters are found for higher harmonic numbers. Finally, emission ratios are calculated from absorption results and the reciprocity relations. Potential applications for alpha diagnostics are discussed.

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CQL3D Calculations of the Radial Profiles of Lower Hybrid Current Drive*

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Lower hybrid current drive (LHCD) can be used to control the radial profile of tokamak current, providing a means to stabilize MHD modes and possibly accessing the second stability region. Accurate calculations of the radial profiles of driven current are required for assessing this possibility, for interpretation of experiments, and for design of new experiments. We use a comprehensive 3+D Fokker-Planck (FP) calculation of LH deposition to achieve high levels of realism in simulation of these experiments. The code combines the CQL(3D) relativistic, bounce-averaged FP code [1] with a new calculation of quasilinear diffusion due to energy traveling along rays, the latter obtained from the RAYLH code [2]. The FP code is 2D in momentum space and is run simultaneously on a radial array of plasma flux surfaces. Poloidal angle variations are accounted for in the bounce-averaging; spatial geometry is 2D in the tokamak cross-section. The present code extends previous calculations [3] by the inclusion of 2D in momentum space (rather than 1D) Fokker-Planck results, thereby removing the requirement for an important ad hoc assumption of a perpendicular electron temperature, and in the bounce-averaged effects.

Current profile control scenarios for the ASDEX experiment [4], and for the future PBX experiment, are examined. Emphasis is on high-power, low-$\eta_{\parallel}$ injection for maximum current drive efficiency, combined with low-power, high-$\eta_{\parallel}$ spectra; the latter spectra single pass damp thereby providing a "seed" tail electron distribution at intermediate radii and directing deposition of the low-$\eta_{\parallel}$ power to that location.

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Resistive MHD Stability Analysis of TFTR Supershots*

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In the enhanced confinement regime in TFTR (supershots) it is observed experimentally that distinct modes of instability can occur in different discharges although the equilibrium configurations inferred from each discharge are nominally very similar. For example, some supershot discharges exhibit a 2/1 mode, others where the instability is 3/2 and sometimes no mode at all. These instabilities, when they occur, can mar the confinement properties of the discharge. Some of these supershot equilibria have been analysed using a linear resistive MHD stability code known as ARES. This code solves the full resistive MHD equations using magnetic flux coordinates and assuming incompressible perturbations. Equilibrium pressure and q profiles are obtained initially from the TRANSP analysis code; these are subsequently varied to study the effects which lead to the observed instabilities. Initial results are presented which show that it is possible to reproduce the observed behaviour computationally. The instabilities are tearing modes whose growth rates and the circumstances of their existence depend sensitively on the pressure distribution in the vicinity of resonant surfaces.

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HYDROGEN RECYCLING WITH RESONANCE LINE REABSORPTION

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The ionisation dynamics of hydrogen recycled at a divertor plate is considered, with particular emphasis on the effect of resonance line reabsorption. Computer simulations of hydrogen ionisation and transport in tokamaks are generally made assuming an optically thin medium. i.e., photons radiated by the excited atoms are assumed to escape without a significant probability of being reabsorbed. This assumption may become invalid for conditions characteristic of actual tokamak edge plasmas. As an example, the radiation from the Lyman α line has a significant probability of being reabsorbed after going through $\simeq 5\times10^{13}$ neutral atoms per cm^2. With the high recycling schemes presently considered for ITER, this could correspond to physical distances of order a few millimeters only. In this paper, the effect of resonant photoexcitation on the excitation and ionisation dynamics of atomic hydrogen is considered. For simplicity, the plasma density and temperature are assumed to be constant and uniform. Opacity effects are only considered for the Lyman α line. The model otherwise accounts for electron impact excitation and ionisation, and for charge exchange from the ground and excited states. Photoexcitation is found to increase the relative population of excited states, thus leading to an enhancement in the net ionisation rate and a substantial reduction in the total energy radiated per atom.

Plasma Parameters and Scaling Laws for Mirrortron Ion Accelerators*

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The Mirrortron [1] is an ion accelerator based on the space-charge potentials produced in a mirror-confined hot-electron plasma subjected to a localized pulsed mirror. Ion inertia plus the quasi-neutrality condition leads to the generation of localized regions of space-charge potential that can be used to accelerate ions. These plasma constraints (quasi-neutrality and ion inertia) lead to scaling laws for such accelerators that have been evaluated theoretically. In particular, the achievable acceleration gradients can be shown to depend linearly on the charge-to-mass ratio of the background plasma ions. Having satisfied this constraint they then depend only on the plasma beta value (as the square-root), on ε, the ratio of the Debye length to the plasma radius, and on the magnitude of pulsed field. This means that provided β and ε are held constant, high gradients may be achieved even in the limit that the pulsed field is small compared to the background field. In this limit most of the energy to accelerate the ions can be derived from the stored kinetic energy of the electrons, rather than from the pulsed field itself. Advantage can be taken of this circumstance in the design of a practical accelerator.

The presence of the background plasma will reduce the self-space-charge effects of the accelerated ions. The magnitude of this screening can be estimated using the same theoretical model used to calculate the accelerating fields. Scaling laws for this effect have also been derived.

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Direct Conversion of Muon Catalyzed Fusion Energy*

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Abstract

In this paper a method of direct conversion of muon catalyzed fusion (MCF) energy is proposed in order to reduce the cost of muon production. This MCF concept is based on a pellet composed of many thin solid deuterium-tritium (DT) rods encircled by a metallic circuit immersed in a magnetic field. The direct energy conversion is the result of the heating of the pellet by beam injection and fusion alphas. The expanding DT rods causes the change of magnetic flux linked by the circuit. Our calculation shows that the direct conversion method reduces the cost of one muon by a factor of approximately 2.5 over the previous methods. The present method is compatible with a reactor using the pellet concept, where the muon sticking is reduced by the ion cyclotron resonance heating and the confinement of the exploding pellet is handled by magnetic fields and the coronal plasma. A few other configurations will be discussed.

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Symplectic Integration of Guiding-Center Orbits

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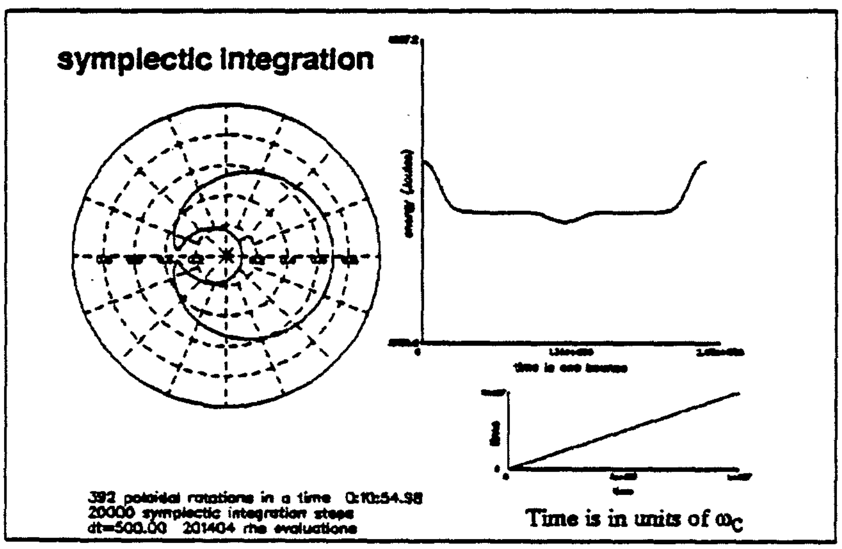
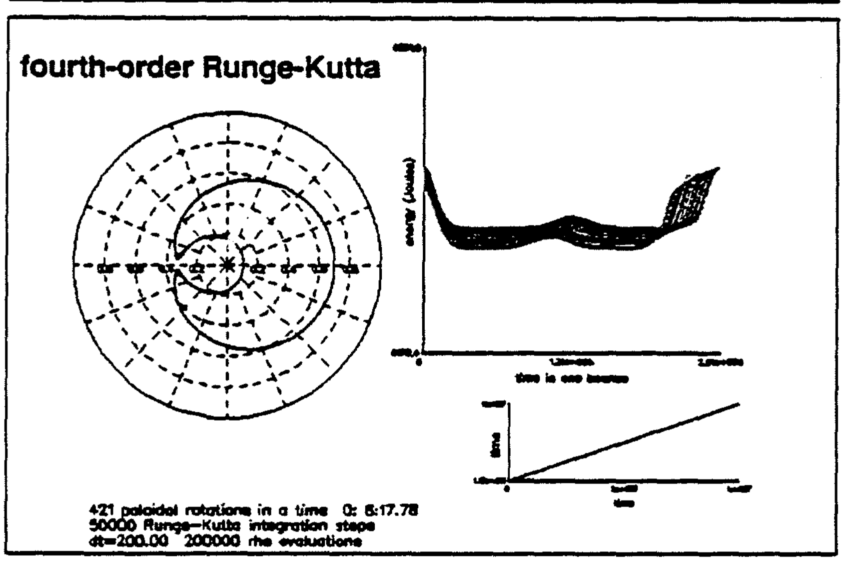
In order to study the full thermalization of alpha particles in a fusion reactor, the orbit must be followed for many thousands of times around the machine. Conventional integration techniques are not suited to correctly predicting the long-term behiviour of such orbits.

John Cary[1] has developed a second-order symplectic integration scheme that explicitly preserves the Poincaré integral invariants to machine accuracy. The easiest way of developing a symplectic integration method[2] is to use a generating function to advance the integration from one time step to the next. Unfortunately, the resulting algorithm is implicit, and a non-linear equation must be solved at each time step. An almost superconvergent Newton solver is used to facilitate this process.

We have applied the symplectic integration method to integrate guiding- center orbits in Boozer coordinates using the canonical variables θ, φ, P_θ and P_φ. Initially we have studied tokamak orbits in a model field, and compared the symplectic method (SM) to fourth order Runge-Kutta (RK4) integration.

To perform a fair comparison, we require the same number of evaluations of the right-hand side of the differential equations. The superior results of the SM are illustrated. As the right-hand side of the equations becomes more complicated, the slight time advantage of the RK4 method will decrease. The top picture shows the orbit integrated using the symplectic method. The fourth order Runge-Kutta method is used in the bottom picture.





The smearing of the energy is quite apparent with the RK4 method. Although the energy is not strictly a constant because we plot only the lowest order expression for the true energy, it is strictly periodic with the SM. Using the RK4 method, the slight displacement of the banana tip causes the period of the orbit to vary. This, together with the fact that the initial pitch angle must be changed slightly in the two cases in order to achieve a similar orbit, accounts for difference in the number of poloidal transits.

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KINETIC EFFECTS ON ION TEMPERATURE GRADIENT DRIVEN TURBULENCE

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It is well known that kinetic effects can significantly modify the linear growth rate of the ion temperature gradient driven instability (or "η_i instability"), especially near marginal stability. Similarly, the nonlinearities which cause saturation of the instability become kinetic, rather than fluid-like, in nature. For example, the trajectories of ions which $\vec{E} \times \vec{B}$ drift and stream freely parallel to the magnetic field are different for different values of the parallel velocity. The role of such effects in the self-consistent evolution of ion temperature gradient driven turbulence is examined by comparing gyrokinetic particle simulations with pseudospectral fluid simulations made for the same values of the physical parameters. The parameters used are such that there is a significant fluid-unstable range in wavenumber space. The fluid models used generalize the equations of Horton, Estes, and, Biskamp[3] to allow for anisotropic pressure evolution and terms which model linear kinetic effects. Detailed results of the comparison and a discussion of their implications will be presented.

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The Role of the Internal Kink Mode in Experiments

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The internal kink mode has been implicated in explaining the *fishbones*, a form of MHD activity associated with fast ion losses. The correlation has been mostly circumstantial, based on modelling the experimental plasma discharge with a theoretical equilibrium model and its stability analysis. A major difficulty has been the lack of precise data on the current profiles, especially in the interior of the plasma. This strongly affects the ability to predict the stability of the internal kink mode, which is critically dependent on the value of q at the magnetic axis as well as the shear in that region. Recent diagnostic developments[1] have made it possible to measure th q–profile directly and have therefore made it possible to eliminate this uncertainty. We shall report on the stability of the PBX-M tokamak for a series of discharges aimed at understanding the role of the plasma shape in determining the stability of the internal kink mode.

Acknowledgments. This work was supported by the United States Department of Energy Contract No. DE–AC02–76–CHO3073.

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Numerical Determination and Experimental Measurement of Vacuum Fields for 3-D ICRH Antenna Configurations.*

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The 3-D ARGUS code has been used to determine the vacuum fields of the Phaedrus-B antenna at U. of Wisconsin with considerable success. A similar analysis is presently being performed for the TFTR antenna at PPPL. The ARGUS simulation models realistically the geometrical complexities of an antenna configuration which may consist of current strap(s), Faraday shield, and an RF box as in TFTR or sideshields and endcaps as in Phaedrus-B. The time-dependent calculation produces self-consistent currents and fields throughout the entire antenna structure. From these, the effect of an individual antenna component can be examined and its impact on the overall antenna design and/or edge-plasma interaction can be evaluated. The Phaedrus-B simulation has served to validate the code since excellent agreement is found between numerical results and experimental data. We will present a detailed comparison of the near field pattern and strap current distribution. The present TFTR simulation focuses on the phasing between the current straps and the field spectra generated by ARGUS will be compared to those inferred from experimental measurements.

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Time Evolution of Tokamaks Based on the Braginskii Model*

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By appropriate scaling the time dependent two-fluid Braginskii model system is solved with an expansion in aspect ratio. The unknowns T_i, T_e, n, λ_i, and λ_e, where λ_α is the stream function for the electron and ion flow, and ψ satisfy an explicit, closed system of equations. The time evolution is in the time scale $\tau_e m_i/m_e \sim 50$ ms for a moderate sized moderately hot plasma. On this time scale time independent solutions without external sources are considered.

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Gyrokinetic Particle Simulation of Gradient-Driven Microinstabilities

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Gyrokinetic particle simulation of gradient-driven microinstabilities have been carried out in two-dimensional slab geometry. The purpose of the study is to understand the effects of magnetic perturbations and impurities on the linear and nonlinear evolution of drift waves and ion temperature gradient drift (η_i) modes.

To account for the magnetic perturbations, we have developed a 2D particle code based on the finite-β gyrokinetic formalism,[1] in which the quiet start technique of Hammersley[2] and the weighted scheme for the partially linearized electrons[3] have been used. As expected, the linear growth rates for these instabilities are reduced by the presence of the finite-β perturbations. Their effects on the nonlinear saturation, and the particle and energy transport will be reported.

The issue of inward particle flux of the impurities in the presence of η_i-modes has also been investigated. The results indicate that the impurities tend to enhance the saturation amplitude of the instability. Moreover, the inward particle flux persists at a level comparable to but somewhat smaller than the quasilinear value long after the nonlinear saturation. Most interestingly, the observed glob formation for the impurities seems to indicate that the inward particle flux may be convective rather than diffusive in nature.

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Transition to H-Mode Behavior Produced by Radial Currents*

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Recent experiments in the CCT tokamak by Taylor, et. al.,[1] have demonstrated that a transition from L-mode to H-mode behavior can be triggered when a radial current flows to an internal electrode which is externally biased. The present study aims to elucidate the principal physical processes associated with such a phenomenon without introducing undue complexity. For this purpose a relatively simple transport code has been developed which includes plasma production by neutral fueling, confinement imperfections due to symmetry-breaking forces, and zeroth-order transport set by Bohm diffusion. An external current injector can be placed at an arbitrary radial location, and the resulting plasma density profile and radial electric field are determined self-consistently. The enhanced confinement regime is obtained by linking the Bohm-diffusion coefficient to the value of the local electric field. It is found that at a certain value of injected current (~ 10 Amps for CCT parameters) the L-mode type equilibrium with a gentle edge profile is lost and a new profile is achieved that possesses a sharp edge gradient and has a higher central density for fixed neutral fueling (i.e., τ_p increases). The electric field is now concentrated over a small spatial region near the wall, with a weaker plateau extending inwards to the radial position of the injector. A reduction in the injected current permits a new set of equilibria to be accessed, having lower peak density (as in L-mode), but with a sharp edge gradient supported by a radial electric field, i.e., the transport model exhibits a bifurcation. Results of the code are compared with experimental observations to test the validity of the various approximations.

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EFFECT OF VELOCITY FIELDS ON SATURATED ISLAND WIDTHS*

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We describe results from a quasilinear theory of saturated tearing modes in a slab, in the presence of poloidal and toroidal velocity fields. The theory is an extension of the recent work of Zakharov[1], who considered the zero velocity limit. Expansion in the neighborhood of the island allows us to determine the quasilinear effect for arbitrary velocity profiles, given Δ'. We also obtain global solutions for particular velocity profiles, giving an indication of how Δ' is affected by the velocity.

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Stabilization of Ballooning Modes by Energetic Ions in TFTR Supershots

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It has been suggested by Rosenbluth and co-workers[1] that the introduction of highly energetic trapped particles in the outer and bad-curvature region of a tokamak may allow direct stable access to the second regime of stability. Further studies have indicated that careful programming of the pressure and q–profiles is necessary in order to avoid the instabilities associated with drift–reversal.[2–4] For most tokamaks, it is usually necessary to raise the axis–q to a value larger than unity to obtain stable access trajectories to the second regime. This means that energetic particle stabilization is most effective when it is used in tandem with some form of q-programming, and it can reduce the burden on q-programming as a sole method of transition to the second regime.

In the present study, we explore the possibility of stabilizing ballooning modes in TFTR supershots by using energetic ions generated by ICRF heating. We show that, by using energetic ions, ballooning modes can be stabilized up to average beta values two to three times typically observed in supershots. This can be achieved without optimizing the pressure profile, but needs a central q of approximately 1.5. The average hot-particle beta is of the same order as the core plasma beta. Detailed profile information and estimates of hot-particle energy will be given.

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Gyrokinetic Particle Simulations of Electrostatic Plasma Turbulence

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We present current research in low-frequency plasma phenomena using gyrokinetic techniques. We use an efficient 2D electrostatic slab-model gyrokinetic particle-in-cell code as a tool to study η_i and universal modes with and without shear. With the use of new vectorization techniques[1] and electron subcycling,[2] we have produced a code efficient enough to run simulations with substantially more particles, grid cells, and timesteps than previous research.[3–4] We compare these earlier results with our new simulations. We are applying gyrokinetic simulations to a variety of problems: investigation of the effects on η_i turbulence of non-Maxwellian distributions, representative of neutral-beam- or strongly-RF-heated plasmas; testing of scaling laws derived from invariance properties (generalizations of Ref. 5); and assessment of plasma turbulence theories. In this last application we study the validity of the primitive fluid equations and various approximations made in closure schemes (*e.g.*, Ref. 6 and Ref. 7). We discuss the status of our simulations and present results on a variety of these topics.

We are currently developing more advanced gyrokinetic simulations in both 2D and 3D. We apply semi-implicit methods and orbit-averaging techniques to the problem of producing practical electromagnetic gyrokinetic simulation codes. In parallel, we are developing a flexible diagnostic capability for the code which will allow comparison with experimental measurements and quantities of interest in the theories. This effort makes use of the Basis physics code system on Sun workstations and Crays, and the NCSA data imaging software.

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Sheath-Plasma Modes and Anomalous Loading in IBW Experiments*

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Sheaths exist whenever plasma contacts a metal surface. The resulting gradients in the equilibrium densities of electrons and ions, allow a class of electrostatic oscillations, sheath-plasma modes, to be supported. These modes are entirely different from those that occur in an unbounded plasma. Whereas the latter have the property that the local dielectric response function vanishes, the former do not. In the small wavenumber limit, one branch of the sheath-plasma modes reduces to the sheath-plasma resonance[1]. In the large wavenumber limit, the modes typically reduce to surface waves localized near the sheaths. In a model geometry that is relevant to ion Bernstein wave (IBW) antennas in tokamaks, it is shown that in addition to the expected IBW modes, the system supports sheath-plasma modes which may be parasitically excited by the antenna.

As a second part of our study, it is speculated that sheath-plasma modes driven unstable by an IBW antenna can extract a large amount of energy and hence contribute to the observed anomalous loading in IBW heating experiments. The instability results from a type of parametric coupling, investigated previously in a specialized limit.[2] Basically, the oscillations of the sheath boundaries at the rf drive frequency pump energy into the sheath-plasma modes. This phenomenon is seen both analytically and from particle simulations. The power flux launched into the sheath-plasma modes relative to that launched into the IBW branch will be discussed.

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Nonlinear Saturation of Ideal Interchange Modes *

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Localized interchange modes in a "cylindrical tokamak" may grow to saturate at certain new helical equilibria. We study these equilibria using the Lagrangian approach that ensures conservation of flux surfaces.

Highly perturbed "nonlinear" layers are formed in these saturated states around resonant magnetic surfaces. The width of such a layer is approximately equal to the distance of the furthest maximum of linear eigenfunction from the resonant surface and is almost independent of the parity of the mode. However, the energy of saturated state for ballooning parity mode is found to be distinctly lower than that for tearing parity perturbation.

Within the nonlinear layer the sheet currents on the resonant surface produce island-like magnetic structures. These may account for fast reconnection and/or enhanced transport across such layers in dissipative systems.

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Abstract for Williamsburg Sherwood Meeting

TIGHT ASPECT RATIO TOKAMAKS

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ABSTRACT

Theoretical studies indicate that a tokamak plasma should exhibit significantly different physics behaviour as the aspect ratio (A = R / a) reduces below about 2. This includes changes in equilibrium properties, enabling high plasma currents and high beta values (typically 20-30%); modified MHD behaviour, with the possible partial or complete stabilisation of some tearing modes; and changes in resistivity and transport, due to the significant trapped particle population.

In order to investigate this behaviour, two experiments in the UK are being progressed, which feature different solutions to the problem of providing the plasma current at tight aspect ratio - when there is very little space for a conventional ohmic solenoid.

Recently Culham has begun to build the START experiment (Small Tight Aspect Ratio Tokamak) which is designed to overcome the plasma current problem by inducing a small plasma at large radius, and then compressing the plasma to a final configuration of very tight aspect ratio; flux conservation during this process will produce a substantial increase in plasma current. On completion in late 1990, it is hoped that START will enable the study of quite hot, relatively high current plasmas at aspect ratio ~ 1.2. Simulations of the properties expected in such plasmas will be presented.

At UMIST, the existing SPHEX spheromak experiment [1] has been modified by the insertion of a conducting rod along the geometric axis. The rod can be energised to carry a current of up to 60kA in either sense; when this current is parallel to the spheromak gun current, this is sufficient to produce a tokamak-like q-profile for gun current Ig up to at least 100kA, assuming the configuration to be a fully-relaxed Taylor minimum-energy state. This is therefore another way of forming a very tight-aspect-ratio tokamak configuration. Although the plasma is cold in comparison to that predicted for the START experiment, the preliminary results from SPHEX -tokamak show that energising the rod appears to increase the current amplification ratio; to destroy the coherence of the regular 25kHz oscillation seen in the spheromak and reduce its amplitude; and to change the critical value of μ_g required for plasma ejection from the gun.

Considerations of the possible reactor applications of tight-aspect-ratio devices will be presented, and it is shown that for a copper central column there is a minimum aspect ratio A, determined by the fraction of re-circulating power economically viable and the beta value achievable.

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SHERWOOD THEORY MEETING 1990

2-D Gyroviscous MHD—Stability Analysis*

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We present a Lagrangian density, that generalizes early work by Newcomb,[1] for a class of compressible gyroviscous systems characterized by a nondissipative stress tensor in the equation of motion. Starting from the variational principle we derive an expression for the energy of small perturbations by Legendre transformation. This leads us to a generalized energy principle δW, that includes new terms arising from the gyroviscosity. Stability conditions for static and stationary equilibria will be presented.

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DISSIPATIVE TRAPPED ELECTRON DRIFT WAVE TURBULENCE*

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Trapped electron modes can play an important role in enhancing losses in a toroidal confinement device.[1] They could be one of the causes for the deterioration of confinement with beta in tokamaks. Here, we consider the dissipative trapped electron drift wave turbulence. The model equations are the continuity equation and the parallel momentum balance equation. In the continuity equation, the non-adiabatic contribution from the electron density is approximated by the solution of the linear drift kinetic equation in the limit $\omega_b \gg \nu_{eff} > \omega$, in the same way as Catto and Tsang.[2] In this approximation, the electrons are laminar and there is a second-order time derivative in the continuity equation introduced by the nonadiabatic electron component. This second-order derivative introduces a fast non-physical linear time scale. In order to get rid of the spurious root, the time derivatives from the nonadiabatic component are replaced by the time derivatives of the solution of the linear equations. This approach is similar to the one used by Crotinger.[3] A new code has been implemented to solve the nonlinear equations. It uses the same numerical methods as FAR,[4] for a sheared slab geometry. Results of the linear stability analysis and available results of the nonlinear multihelicity calculations will be presented at the meeting.

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POLOIDAL PLASMA ROTATION IN TOKAMAKS*

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It is found experimentally that the poloidal plasma rotation speed increases at the onset of the L-H transition in tokamaks. To understand this phenomenon, a model based on balancing the ion orbit loss flux with the poloidal (parallel) viscosity driven flux was proposed. Here, we extend the model to include the compressibility term $(\vec{\nabla} \cdot \vec{V})$ in the parallel viscosity and the convective nonlinear term $(\vec{V} \cdot \vec{\nabla}\vec{V})$ in the parallel force balance equation. Here, V is the plasma flow velocity. We show explicitly that an effective parallel viscosity $\langle \vec{B} \cdot \vec{\nabla} \cdot \overleftrightarrow{\Pi}_{\text{eff}} \rangle$ can be defined to combine the effects of both $\langle N\vec{B} \cdot \vec{V} \cdot \vec{\nabla}\vec{V} \rangle$ and $\langle \vec{B} \cdot \vec{\nabla} \cdot \overleftrightarrow{\Pi} \rangle$, where N is plasma density and the angular brackets denote flux surface average. It is shown that $\langle \vec{B} \cdot \vec{\nabla} \cdot \overleftrightarrow{\Pi}_{\text{eff}} \rangle$ is positive definite. To evaluate $\langle \vec{B} \cdot \vec{\nabla} \cdot \overleftrightarrow{\Pi}_{\text{eff}} \rangle$, one needs to calculate the density variation along the magnetic field line. This can be accomplished by solving the nonlinear local force balance equation along the field line using the parallel viscosity as the dominant dissipation mechanism. In the large aspect ratio limit, one can solve analytically the linearized equation to obtain a consistent solution. In the finite aspect ratio limit, the equation is solved numerically. The implications on the L-H transition will be discussed.

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Reciprocity Relations for Coupled Rational Surfaces

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We consider the problem of calculating the stability of fusion devices toward nonideal MHD instabilities involving more than one rational surface, such as double tearing modes in cylindrical geometry, toroidally coupled tearing modes, or resistive ballooning modes, by the method of asymptotic matching.[1,2,3] One needs to calculate a response matrix giving the amplitudes of odd and even ideal "small" solutions (in the sense of Frobenius) on all surfaces driven by odd and even unit ideal "large" solutions imposed on each surface in turn. This matrix represents a complete generalization of the delta-prime of simple tearing theory, and can be matched to any model of the inner layers, including nonlinear theories in the thin island approximation.

We present a new variational principle for the response matrix which allows us to prove symmetry relations between the off-diagonal elements of the response tensor. These form a kind of reciprocity relation in which the response at one surface driven by a virtual nonideal instability at another surface is related to the response at the second surface driven from the first. This principle also forms the basis of a Galerkin method[4,5] for calculating the response matrix using finite elements, for which convergence results will be presented.

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Sherwood Theory Meeting
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Williamsburg, Virginia

Ballooning Modes on Finite Length Field Lines*

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Magnetic field lines which intersect the plasma boundary are common in a divertor geometry, where field lines intersect the divertor plates, as well as in space plasma configurations such as a magnetosphere. When ballooning modes are discussed in such situations, it is also necessary to discuss the waves reflected from the boundary. We show that, in addition to a reflected ballooning mode, there is an evanescent fast wave which decays rapidly off the boundary and can therefore be ignored in the usual ballooning expansion.

We have derived the appropriate ballooning boundary conditions for perfectly conducting divertor plates (or planets), for conducting plates (or an ionosphere), and for insulating plates (or an atmosphere). The last case yields non-obvious boundary conditions which, interestingly, generate a self-adjoint stability problem. We give this problem a variational formulation, and show that it admits test functions which may be interpreted as implying an "interchange" motion and yield a necessary condition for stability.

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Abstract
for 1990 Sherwood Theory Meeting

Effects of Non-uniform Rotation on The Ion Temperature Gradient and Trapped Particle Instabilities*

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Effects of rotation (in the diamagnetic drift direction) and its shear on the Ion Temperature Gradient Instability have been investigated. The analysis is done in a magnetic shearless slab geometry with adiabatic electrons and fully kinetic ions in the presence of non-uniform equilibrium electric field. The shear in rotation causes a shift in cyclotron frequency which affects the threshold of the instability. The gradient of the rotational shear causes the well known FLR modification which also affects the instability threshold. It is found that a positive gradient of the rotational shear is stabilizing. The assumption of adiabatic electrons rules out any centrifugal drive due to rotation. Retention of a small non-adiabatic electron response due to Landau resonance, causes a weak centrifugal drive for the mode.

In a curvature driven trapped particle instability, non-adiabatic electron and ion responses in the presence of rotation cause a strong centrifugal drive, which is experimentally confirmed. However, contrary to intuition, the global ($m = 1$) mode is experimentally seen to survive a strong rotational shear.

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ENERGETIC PARTICLES AND MHD MODES*

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The effect of energetic particles on MHD modes is a major issue in present-day tokamaks and future ignited tokamaks. In particular, we address the stability problems of (1) the ideal MHD internal kink modes and the resonant "fishbone" internal modes, and (2) the toroidicity-induced Alfven eigenmodes (TAE). For low frequency MHD modes (internal kinks and fishbone modes) there are two destabilizing mechanisms due to energetic trapped particles. Firstly, for low frequency MHD modes with $\omega << \omega_d$ (ω_d is the trapped particle bounce-averaged magnetic drift frequency), the trapped particles give a negative contribution to the potential energy if $(\omega_*/\omega_d) < 0$ (ω_* is the trapped particle diamagnetic drift frequency) and have a destabilizing effect. Secondly, if $\omega \approx \omega_d$, then the energetic trapped particle motion is no longer rigid with respect to the MHD perturbation and wave particle resonance can occur. Magnetic drift resonant "fishbone" instabilities can be excited by tapping free energy from the energetic trapped particle pressure nonuniformity. Depending on the energetic particle pitch angle distribution, a stability window for the internal kink mode and the fishbone mode in the energetic particle beta space exists even in the absence of core ion finite Larmor radius effect. For the high frequency TAE modes with $\omega \approx \omega_t$, ω_b (ω_t is the circulating particle transit frequency, and ω_b is the trapped particle bounce frequency), the TAE modes can be driven unstable by the circulating and trapped energetic particles resonanting with the background waves via inverse Landau damping. The typical growth rate of the TAE mode for ITER parameters can be in the order of $10^{-2}\omega_A$, where ω_A is the Alfven frequency.

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MHD Simulations of the Direct Energy Extraction from Rotating FRC Plasmas*

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A small population of energetic particles in a field reversed plasma configuration provides an electrical coupling between the dense bulk plasma within the separatrix and a low density plasma exterior to the separatrix. The fusion plasma in an FRC is "selectively" confined, giving rise to spinning and reinforcement of field reversal.[1] The coupling tends to bring the coronal plasma up to the same rotation rate Ω as the plasma within the separatrix. The rotation of the coronal plasma leads to a twisting of the external field lines if these field lines connect with conducting end plates. This twisting corresponds to flow of current out the axis of the system. This can be directly convertible to electric energy in the outside circuit.[2] Using an axisymmetric MHD simulation code, we have modeled the envisioned phenomena. The simulations show the critical stages of the axial outflow of current, the coupling between internal and coronal plasmas, braking of the internal plasma spin, and a twisted magnetic structure.

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Threedimensional MHD Computation of Global Toroidal modes

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It is well known that tokamaks exhibit saw-tooth oscillations and disruption instabilities and that effects of toroidal mode coupling appear in these phenomena [1]. In order to investigate the MHD mode structure and propagation for instance in the toroidal ASDEX device [2], it is necessary to solve the ideal and resistive MHD equations. Such solutions are known in cylindrical coordinates and the effect of the toroidal curvature has been taken into account by series in powers of the inverse aspect ratio [2]. Such series, if restricted to the first order in the inverse aspect ratio can, however, not be used for compact devices with small aspect ratio. In such a case exact global solutions have to be considered.
Then the problem arises to satisfy the boundary conditions on toroidal surfaces which is difficult since toroidal coordinates do not allow the separation of the MHD wave equations. We thus have an unseparable boundary value problem. It is, however, possible to solve the problem analytically by using the general (separable) solution in cylindrical coordinates. The general solution of a partial differential equation of second order contains 2 arbitrary functions. If one expands these arbitrary functions into series according to the cylindrical modes, one obtains a double infinite set of coefficients (partial amplitudes of the modes). These coefficients can be used to construct a global analytical solution satisfying the boundary conditions on the toroidal surface by a method having been applied with success for 2 dimensional MHD modes [3].

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Electron Transport from Drift-Wave Turbulence Driven by Temperature Gradient*

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It has been proposed[1] that the drift-wave turbulence driven by the electron temperature gradient explains the anomalous transport of the heat observed in the tokamaks. The drift wave is linearly unstable at the scale of the electron gyroradius and the dominant fluctuation energy in the saturated state is shown to be at the scale of the collisionless skin depth c/ω_{pe}. The local electron thermal conductivity χ_e obtained from mixing length estimates provides a reasonable explanation to the experimental observations.[2,3] However, in many cases, the importance of the balance between the various energies—the kinetic, the field, and the thermal energy—has not been stressed properly. In this work, more emphasis is put on the energy balance between the fluctuation energies and the background thermal energy. The two energy densities of the fluctuation energies and the thermal energy may differ by orders of magnitudes, but are freely exchanged with each other through the transfer terms calculated here. It is shown that the fluctuation energy is produced due to the turbulent heat flow across the nonuniform mean pressure $\nabla \overline{p_e}$ and because of the magnetic-field nonuniformity $\nabla \ln B^2$. In the steady state, globally, these turbulence production terms are balanced by the absorption of the fluctuation energy at small scales due to the classical dissipations.

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CURRENT DRIVE SCENARIO IN A FLEXIBLE HELIAC

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TJ-II is characterized by a high degree of flexibility, i. e. by changing the ratio of currents in its hard core the properties of the magnetic configurations obtained can be very different in terms of the rotational transform ($0.22 \leq \iota(0)/4 \leq 0.628$), magnetic well $\leq 6\%$ (and therefore indentation of the bean shaped plasma) , plasma radius ($10 \leq a \leq 25$ cm.) and plasma position [1].

Ray tracing calculations in the Flexible Heliac TJ-II have already been made applied to a "reference" TJ-II magnetic configuration of rotational transform equal to 0.36, plasma radius ≈ 20 cm and "average" indentation. The results obtained in such a work have given an optimum microwave launching position, illumination angle and value of absorbed power [2].

In this work the current generated in the Flexible Heliac TJ-II during electron cyclotron heating is calculated for low power density, using very different magnetic configurations. Electron cyclotron absorption is computed using a weakly relativistic model for a Maxwellian distribution function. The current generated is then evaluated by the Fisch and Boozer formula [2]. This expression allows a fast estimate of the current induced by the microwaves and therefore can be included in ray tracing codes . The results obtained in this way are accurate within the validity of the eikonal theory and as long as quasi-linear effects are negligible [4].

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