SHERWOOD '89

1989 INTERNATIONAL

SHERWOOD THEORY CONFERENCE

APRIL 3-5, 1989

SAN ANTONIO, TX

Saralyn Stewart

1989

THE INTERNATIONAL SHERWOOD THEORY CONFERENCE

APRIL 3-5, 1989
THE GUNTER HOTEL
SAN ANTONIO, TEXAS

Under the auspices of

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GENERAL INFORMATION

- 239 papers were submitted, of which 12 were selected for oral presentation.
- The Review papers will be presented in the Crystal Ballroom, Monday and Tuesday mornings beginning at 8:30 a.m..
- All oral papers will be presented in the Crystal Ballroom, Monday and Tuesday mornings beginning at 9:30 a.m. Each talk will be 25 minutes in length plus 5 minutes for discussion.
- A special session on Transport and Confinement will be held on Monday evening beginning at 8:00 p.m. in the Crystal Ballroom.
- Poster sessions will be held on the Gunter Terrace Monday afternoon, Tuesday evening, and Wednesday morning.
- A reception will be held on Monday evening 6:00 - 8:00 p.m. in the Magnolia and Blue Bonnet Rooms.
- Refreshments will be served consisting of coffee and tea during the morning sessions; beer and soft drinks during the afternoon and evening sessions.
- Requests for special meetings should be made with Saralyn Stewart at the Conference Registration Desk.

1989 SHERWOOD THEORY CONFERENCE SCHEDULE

THE GUNTER HOTEL

SAN ANTONIO, TEXAS

APRIL 3 - 5, 1989

REGISTRATION

April 2, 1989 - 6:00 - 10:00 PM
April 3, 1989 - 7:45 AM - 5:00 PM
April 4, 1989 - 7:45 AM - 12:00 PM and 7:00 PM - 9:00 PM
April 5, 1989 - 8:00AM - 10:00AM
Mezzanine

ORAL AND POSTER SESSION SCHEDULE

Reviews and Orals - Crystal Ballroom

Posters - Gunter Terrace

Monday, April 3, 1989

Welcome - 8:20 AM
1A - 8:30 AM - Review Paper
1B - 9:30 AM - 12:30PM - Oral Sessions
12:30 - 2:00 PM - LUNCH BREAK
1C - 2:00 - 4:00 PM - Poster Session
1D - 4:00 - 6:00 PM - Poster Session
6:00 - 8:00 PM - RECEPTION
1E - 8:00 - 10:00 PM - Transport and Confinement Special Session

Tuesday, April 4, 1989

2A - 8:30 AM - Review Paper
2B - 9:30 AM - 12:30 PM - Oral Session
12:30 - 7:00 PM - FREE TIME
2C - 7:00 - 9:00 PM - Poster Session
2D - 9:00 - 11:00 PM - Poster Session

Wednesday, April 5, 1989

3C - 9:00 - 11:00 AM - Poster Session
3D - 11:00 AM - 1:00 PM - Poster Session

Coffee and Tea - 10:00 AM, Monday through Wednesday

Beer and Soft Drinks - 3:00 PM, Monday, 8:00 PM Tuesday

THE INTERNATIONAL SHEWOOD THEORY CONFERENCE
ANNUAL CONTROLLED FUSION THEORY CONFERENCE

Gunter Hotel - San Antonio, Texas
April 3-5, 1989

MONDAY REGISTRATION: 7:45am - 5:00pm

MONDAY MORNING: 8:30am - 12:30pm

WELCOME: 8:20am

1A REVIEW SESSION
8:30am Crystal Ballroom
Presiding: Bruno Coppi

1A1 Experimental Status of the High-Beta, Second Stability Regime in Tokamaks and Stellarators. M. E. Mauel.

1B ORAL SESSION
9:30am Crystal Ballroom
Presiding: F. Troyon

1B1 Information Content of Transient Synchrotron Radiation in Tokamaks. N. J. Fisch and A. H. Kritz.
1B2 Theory of Fast Wave Current Drive for Tokamak Plasmas. S. C. Chiu, V. S. Chan, R. W. Harvey, and M. Porkolab.
1B3 The Status of Statistical Transport Theory for Plasma Turbulence. John A. Krommes.
1B4 Theoretical Studies of Tight Aspect Ratio Tokamaks. A. Sykes, P. S. Haynes, T. C. Hender, T. N. Todd, Y-K. M. Peng, and J. C. Whitson.
1B5 The Stability of the High Density Z-Pinch. A. H. Glasser and R. A. Nebel.
1B6 Soft and Hard Thresholds for Ion Temperature Gradient Driven Transport. A. B. Hassam, T. M. Antonsen, Jr., J. F. Drake, and P. N. Guzdar.

LUNCH 12:30 - 2:00pm

MONDAY AFTERNOON 2:00 - 6:00pm

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

1C1 Numerical Solutions of Statistical Closures for Anisotropic Terry-Horton Dynamics. John C. Bowman and John A. Krommes.
1C2 Simulation of Neutral Helium Transport in Flat Vented Divertors and Limiters. H. H. Abou-Gabal and G. A. Emmert
1C3 Current-Drive by Circularly Polarized Alfven Waves. M. A. Schalit and P. M. Bellan.

1C4 RFP Dynamo and Reversal in MHD and Hall MHD. R. A. Nebel, J. M. Finn, K. L. Sidikman.

1C5 Spectra of Intermittent Magnetic Turbulence. G. Craddock.

1C6 The Rayleigh-Taylor Instability in a Homogeneously Expanding Plasma. S. Cable, R. S. Steinolfson, and T. Tajima.

1C7 Alpha Particle Confinement in Tokamaks. R. B. White, H. E. Mynick, M. S. Chance, and J. Manickam.

1C8 Resistive Helical MHD States with Flow. D. Montgomery, L. Phillips, and M. L. Theobald.

1C9 Three-Dimensional Global Simulation of Electron Drift Mode Turbulence. R. E. Waltz.

1C10 A Simple Method for Calculation of Magnetic Island Widths. James D. Hanson, John R. Cary, Ben Carreras, and V. E. Lynch.

1C11 Dipole Magnetic Field for an Advanced Fuel Reactor. A. Hasegawa.

1C12 Effects of a Toroidal Magnetic Field on the Nonlinear Evolution of the Internal Tilt Mode in an FRC. D. C. Barnes, R. C. Bishop, R. D. Milroy.

1C13 Simulation of the Ion Cyclotron Emission in the JET Tokamak. F. Kazeminejad, R. Bingham, J. M. Dawson, J. N. Leboeuf.

1C14 Computer Simulation of Transport Driven Current in Tokamaks. W. J. Nunan, R. D. Sydora, J. M. Dawson.

1C15 Two-Fluid Theory for Collisional Presheath with Viscosity. B. J. Lee and J. D. Callen.

1C16 Transport Coefficients for the Plasma Thermal Energy and Empirical Scaling "Laws". B. Coppi.

1C17 Relativistic Damping of Electron Cyclotron Waves in Anisotropic Plasmas and Its Application. Kyoko Matsuda and J. Y. Hsu.

1C18 Ideal Stability of Cylindrical Plasma in the Presence of Mass Flow. A. Bondeson and R. Iacono.

1C19 Particle and Heat Pinch Effects in Collisionless Tokamak Discharges. J. Weiland, A. Jarmén and H. Nordman.

1C20 Anomalous Diffusion in Stochastic Magnetic Field. Qi Chen and J. D. Meiss.

1C21 Disruptions in DIII-D. A. D. Turnbull, T. S. Taylor, M. S. Chu, F. J. Helton, W. Howl, L. L. Lao, J. K. Lee, and E. J. Strait.

1C22 A Linearized Resistive MHD Stability Code. T. R. Harley, C. Z. Cheng, and S. C. Jardin.

1C23 The Effect of Parallel Thermal Conductivity on the Stability of Resistive Ballooning Modes. F. Romanelli, J. W. Connor and R. J. Hastie.

1C24 Finite Beta MHD Effects on Thermal Transport. H. R. Strauss.

1C25 The Case for Cold Ions Diffusing Inwards in Tokamaks Too Rapidly to Thermalize. A. A. Ware.

1C26 Effects of Finite Aspect Ratio on High-n Instabilities in Tokamaks. G. Rewoldt and W. M. Tang.

1C27 Theory of Weak Ion Temperature Gradient Driven Turbulence in Flat Density Discharges. D. T. Katt, Y. B. Kim, P. H. Diamond, N. Mattor.

1C28 Bounded Multi-Scale Particle Simulation: The Sheath Problem. S. E. Parker, C. K. Birdsall, A. Friedman and S. L. Ray.

1C29 Localized Profiles of a Self-Focused Optical Beam in a Plasma. T. Kurki-Suonio, P. J. Morrison, and T. Tajima.

1C30 Study of the Magnetic Fluctuations in Resistive Pressure-Gradient-Driven Turbulence. G. S. Lee and B. A. Carreras.

1C31 Electron Transport with Steep Temperature Profiles and Atomic Physics Effects. R. Marchand and J. P. Matte.

1C32 Effects of Temporal and Spatial Bandwidth of a Pump Wave on Parametric Instabilities. Richard L. Berger.

1C33 Ballooning Modes in a Rotating Plasma. E. Hameiri and S. T. Chun.
1C34 Nonlinear Gyrokinetic Moment Equations for Tokamak Plasmas. A. Brizard, L. Chen, and R. B. White.
1C35 Convergence of a Numerical Approximation to the One-Dimensional Vlasov-Poisson System. Stephen Wollman.
1C36 Resistive Interchange Modes and Ion Temperature Gradient Modes in Heliotron/Torsatron. M. Wakatani, H. Sugama, M. Yagi, B. G. Hong, and W. Horton.
1C37 Momentum Transport Process in Plasma Collective Modes. Bruno Coppi.
1C38 Suppression of Wall Field Perturbations in Reversed Field Pinches. M. K. Bevir, R. W. Moses, A. Patel, and H., Y. W. Tsui.

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

1D1 Effect of Density and Temperature Gradients and Shear on the Dipole Vortex Solution of Drift Wave Plasma. X. Su, P. J. Morrison, and W. Horton.
1D2 A Self-Consistent Theory of Radial Transport of Parallel Current by Microturbulence. P. W. Terry, P. H. Diamond.
1D3 Stability of Semicollisional Modes in Divertor Tokamaks. S. Briguglio.
1D4 Ballooning Stability Optimization of Helias Equilibria. J. Nührenberg, R. Zille.
1D5 Parametric Turbulence Effect on LH Heating and Current Drive. Sasha Rubinchik.
1D6 Particle Confinement in Realistic 3D Rotamak Equilibria. P. M. Bellan.
1D7 Theoretical Studies of Profile Control Using Lower Hybrid Current Drive and Electron Cyclotron Resonance Heating. P. T. Bonoli, R. Myer, M. Porkolab, D. T. Blackfield, R. S. Devoto, M. E. Fenstermacher, G. R. Smith, A. H. Kritz.
1D8 One and Two Dimensional Modelling of the RFP Dynamo Effect. D. A. Baker, M. S. Hoyt, K. M. Ling, L. W. Mann, S. C. Jardin.
1D9 Guiding Center Drift in a Rotating Tokamak Plasma. M. D. Calvin, Andrew Ware, and R. D. Hazeltine.
1D10 Three-Dimensional Fluid Computer Calculations of Ion Temperature Gradient Driven Instabilities. J. N. Leboeuf, B. A. Carreras, P. H. Diamond.
1D11 Toroidal Equilibrium of Plasma-Beam Systems. Zensho Yoshida.
1D12 Quiver Kinetics. Peter J. Catto and J. R. Myra.
1D13 Numerical Simulations of Sawteeth in Tokamaks. G. Vlad, A. Bondeson.
1D14 Modification of m=1 Kink Mode Theory Due to Arbitrary Larmor Radius and Hot Electrons. Y. Z. Zhang, H. L. Berk, and S. Mahajan.
1D15 Saturation of a Single Mode in High Energy Particle Driven Systems. H. L. Berk and B. Breizman.
1D16 Delta-F Algorithm for the Integration of the Electrostatic Gyrokinetic Equation. H. V. Wong and H. L. Berk.
1D17 Non-Thermal Modification of the Current Profile in a Tokamak by Electron Cyclotron Heating. V. I. Krivenski, H. L. Berk and Y. Z. Zhang.
1D18 Stability of Magnetic Vortices. G. Rowlands.
1D19 Fast Ion Thermalization in a Hot Deuterium Plasma. T. L. Talley.
1D20 Edge Electric Field Effects on Orbits in Tokamaks and Stellarators. C. L. Hedrick.
1D21 Transport Barrier in Simulations of Eta-i Turbulence. J. F. Drake, P. N. Guzdar, A. Dimits and A. B. Hassam.

1D22 Streamers Driven by the Ion Temperature Gradient Instability. A. M. Dimits, J. F. Drake, P. N. Guzdar, and A. B. Hassam.

1D23 Computation of Magnetic Coordinates and Action-Angle Variables. A. H. Reiman and N. Pomphrey.

1D24 Local Kinetic Stability Analysis of the Ion Temperature Gradient Mode. R. R. Dominguez and M. N. Rosenbluth.

1D25 Radiative Collapse of a Bennett-Relaxed Z-Pinch. Leaf Turner.

1D26 Stability of an FEL E-beam in a Corrugated Waveguide. L. D. Pearlstein and V. K. Neil.

1D27 Transport of Charged Particles Interacting with Coherent Wave-Fields in a Tokamak Plasma. K. Kupfer, A. Bers, and A. K. Ram.

1D28 Collisional Effects on Low Frequency Turbulent Transport of Flux, Particles, and Energy in a FRC. N. A. Krall.

1D29 Three-Dimensional Flux-Tube Dynamics. R. Kinney and T. Tajima.

1D30 Effects of Temperature Anisotrophy, Rotation and Collisions on Eta-i Mode in the Columbia Linear Machine. O. Mathey, A. K. Sen, S. Migliuolo.

1D31 Further Implications for Tokamak Transport from the gBL Transport Formalism. H. E. Mynick and R. E. Duvall.

1D32 Particle-Simulation of Toroidicity-Induced Drift Modes. M. J. LeBrun and T. Tajima.

1D33 Scaling Laws for Resistive Turbulence. W. A. Newcomb.

1D34 TnTau-E Comparisons of Tokamak Reactors of Different Aspect Ratios. Y-K. Martin Peng.

1D35 Bifurcation Theory of Electrostatic Instabilities. C. Kueny, J. D. Crawford, and P. J. Morrison.

1D36 Modifications of the PIES Code to Enhance Convergence. D. A. Monticello and A. H. Reiman.

1D37 Electrical Conductivity in Tokamaks Modified by the Ohmic Loop-Voltage. C. S. Chang.

1D38 Beta Optimization of Ignited Plasmas. J. Manickam.

RECEPTION 6:00pm - 8:00pm

1E TRANSPORT TASK FORCE IMPACT ON THEORY
Crystal Ballroom
8:00pm - 10:00pm

Moderator: D. Baldwin

International Panel: R. Kraichnan, M. N. Rosenbluth, J. B. Taylor, F. Wagner, M. Wakatani.

Invited Speakers include R. Hunter, Jr., J. D. Callen and K. Molvig.

TUESDAY MORNING 8:30 am - 12:30pm

2A REVIEW SESSION
8:30am Crystal Ballroom
Presiding: R. D. Hazeltine

2A1 Can Dynamical Systems Approach Turbulence? P. Holmes.

2B ORAL SESSION
9:30am Crystal Ballroom
Presiding: S. P. Hirshman

2B1 Sawtooth and Other MHD Effects in Tokamaks. W. Park and D. A. Monticello.
2B2 The Theory of Neoclassical Ion Temperature-Gradient-Driven Turbulence. Y. B. Kim, P. H. Diamond, H. Biglari, and J. D. Callen.
2B3 Current Drive via Plasma Waves with Intrinsic Helicity. R. R. Mett and J. A. Tataronis.
2B4 Fast Wave Current Drive in Large Noncircular Tokamaks - A Global Wave Calculation. E. F. Jaeger, D. B. Batchelor, M. D. Carter, and D. W. Swain.
2B5 Drift Fluctuation Driven Transport and Shear in Tokamaks. J. Kesner.
2B6 Electron Temperature Gradient Driven Turbulence and Skin Depth Transport. W. Horton, N. Bekki, and B. G. Hong.

TUESDAY AFTERNOON FREE

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

2C1 Neutral Hydrogen Deposition in a Spheromak Plasma. R. M. Mayo and C. K. Choi.
2C2 Boundary Conditions for the Darwin Model. H. Weitzner and W. S. Lawson.
2C3 Energetic Trapped Effects on the Internal Kink Modes. C. Z. Cheng.
2C4 Comparison of RF codes: ORION, HYPERION, and SHOOT. J. S. Tolliver, E. F. Jaeger, B. A. Carreras, V. E. Lynch, D. B. Batchelor, P. L. Colestock, and D. N. Smithe.
2C5 Theory of High-n Shear Alfvén Gap Mode in Tokamaks. G. Y. Fu, J. W. Van Dam, C. Z. Cheng.
2C6 Bottom Launch for Electron-Cyclotron Current Drive in ITER. Gary R. Smith, G. D. Kerbel, Y. Matsuda, and M. G. McCoy.
2C7 Simulation of Dense Z-Pinch Plasmas. William Grossmann and Alan Mankofsky.
2C8 Magnetic Field Diffusion into High Drift Kinetic Beta Plasma Beams. J. Koga, B. S. Newberger, T. Tajima, and N. Rostoker.
2C9 Simulation of R. F. Driven Plasma Edge. W. S. Lawson and C. K. Birdsall.
2C10 Particle Simulation of Alfven Instabilities in a Neutral-Beam Current-Driven Plasma in a Sheared-Slab Geometry. Y. Matsuda, M. Tanaka and T. Sato.
2C11 Tokamak to Tokamak Variation in Scaling Laws. K. S. Riedel.
2C12 Effect of Arbitrary Larmor Radius on Tearing Modes. S. M. Mahajan and Y. Z. Zhang.

2C13 Design Considerations for Advanced Toroidal Experiments. F. J. Helton, J. M. Greene, and J. W. Helton.

2C14 Tearing Mode Stability of Tokamaks at Finite Beta. M. S. Chu, M. S. Chance, J. M. Greene, and T. H. Jensen.

2C15 Ballooning Modes in Double-Adiabatic and Guiding-Center Plasmas in the Presence of Rotation. X.-H. Wang and A. Bhattacharjee.

2C16 Plasma Current Drive by Helicity Injection in Relaxed States. J. B. Taylor and M. F. Turner.

2C17 The m=1 Internal Kink Mode in a Toroidal Plasma with an Arbitrary q-Profile. H. J. de Blank and T. J. Schep.

2C18 Ultra-Fast Numerical Solutions to the Transport Equations using Variational Techniques. J. P. Freidberg, P. Hakkarainen, J. Kesner, E. Chaniotakis.

2C19 Eta-e Transport, Detached Plasmas and Density Limits. P. N. Guzdar and C. S. Liu.

2C20 Extension of Braginskii Fluid Equations to the Banana-Plateau Regime and Application to Resistive Instabilities. D. A. Spong, K. C. Shaing, B. A. Carreras.

2C21 Nonlocal Energy Transfer Due to Inverse Mode Conversion of Ion Bernstein Waves. Hugo A. Romero and G. J. Morales.

2C22 Low Aspect Ratio Stellarator Optimization. S. P. Hirshman, R. N. Morris, J. A. Rome, C. L. Hedrick, J. F. Lyon.

2C23 Particle Simulations with Predictive Dynamic Load Balancing on Hypercube and Ncube Multiprocessors. Robert W. Huff and John M. Dawson.

2C24 Equations of Motion in Non-Canonical Coordinates for Particle Trajectories in Toroidal Geometries. Alkesh Punjabi, Maria Lam, and Allen Boozer.

2C25 Synchrotron Radiation in Fusion Power Reactors. M. Heindler, A. Nassri, W. Kernbichler, G. H. Miley, F. T. Gratton.

2C26 Modern Software Documentation: A New WEB System for Fortran, Rational Fortran, and C. John A. Krommes.

2C27 MHD Analysis of Peaked Density Profiles Produced by Pellet Injection in JET. L. A. Charlton, L. R. Baylor, B. A. Carreras, J. T. Hogan, G. S. Lee, S. L. Milora, A. Edwards and J. O'Rourke.

2C28 Coherent Structures and Heat Transport in Ion Pressure Gradient Driven Turbulence. M. Ottaviani, F. Romanelli, R. Benzi, M. Briscolini, P. Santangelo, S. Succi.

2C29 Calculation of Hamada Coordinates and its Application in the Moment Equation Approach to Neoclassical Transport Theory for a Large-Aspect-Ratio Tokamak. M. Coronado and J. Galindo.

2C30 The Beta Limit in ATF Due to Local Ideal MHD Instabilities. W. A. Cooper, S. P. Hirshman, D. K. Lee.

2C31 Self-Organization in Sheared Drift-Wave Turbulence. Bruce D. Scott and Hamid Biglari.

2C32 Transport in a Tokamak Based on the Braginskii Model. W. Kerner and Harold Weitzner.

2C33 Energy Transport in JET and Comparison With Theory. T. E. Stringer, F. Tibone.

2C34 Broadening of the Lower Hybrid $N_{\parallel}$ Spectrum by Toroidal Effects. E. Barbato, F. Romanelli.

2C35 Hybrid (Particle-Fluid) Simulations of Low Frequency Plasma Microinstabilities. P. M. Lyster and J-N. Leboeuf.

2C36 Studies in ICRF Heating: (A) Explicit Solutions for Minority Heating; (B) Scattering of a Magnetosonic Wave by Density Turbulence. Huanchun Ye, Daniel R. Cook, and Allan N. Kaufman.

2C37 Nonlinear Solution Branches of Reduced MHD Equations. E. K. Maschke and J. Morros Tosas.

2D POSTER SESSION
Gunter Terrace
9:00 - 11:00pm

2D1 Parametric Decay of Lower Hybrid Waves in Tokamak Plasmas. A. Cardinali, R. Cesario, F. Paoletti.

2D2 Plasma Physics Considerations in the Fusion Ignition Experiment Ignitex. R. Carrera, G. Fu, J. Helton, L. Hively, E. Montalvo, C. Ordonez, M. N. Rosenbluth, S. Tamor, and J. W. Van Dam.

2D3 A Lagrangian Method for Collisional Equations. Giovanni Russo.

2D4 Strong Impurity Transport in Rotating Tokamak Plasma Including Temperature Variations. C. T. Hsu and D. J. Sigmar.

2D5 Nonlinear Interaction of Resistive Modes for $q < 1$ in Tokamaks. J. A. Holmes.

2D6 A Theory of Microwave-Produced Potentials in Plasmas - The Pleiade Experiments Revisited. R. F. Post.

2D7 MHD Modeling of the Fueling of a Tokamak Reactor by Compact Toroids. A. A. Mirin, D. E. Shumaker, and J. H. Hammer.

2D8 Alpha Particle Diagnostics Using Laser Scattering Techniques. R. E. Aamodt.

2D9 Gyroviscous Treatment of Stability in a Field Reversed Configuration. L. C. Steinhauer, and A. Ishida.

2D10 Linear 3D Ideal MHD Global Internal Mode Stability Analysis with the Terpischore Code. W. A. Cooper, D. V. Anderson, R. Gruber, U. Schwenn.

2D11 Matrix Solvers for 3D Ideal MHD Equilibrium and Stability Calculations. D. V. Anderson, W. A. Cooper, R. Gruber and U. Schwenn.

2D12 Transport Timescale Simulation of ITER Operating Scenarios. Thomas B. Kaiser, Neil Pomphrey.

2D13 Dynamical Study of Axisymmetric Stability in Alcator C-Mod. J. J. Ramos, S. W. Haney, D. A. Humphreys, and J. P. Freidberg.

2D14 Stability Beta Limit of Local Modes for the TJ-II Flexible Heliac. A. Varias, C. Alejaldre, Luis Garcia, A. Lopez-Fraguas, B. A. Carreras, N. Dominguez and V. Lynch.

2D15 Bounds on Instability Growth Rates in Tokamaks. T. K. Fowler and P. J. Morrison.

2D16 Thermoelectric Currents in the Scrape-off Layer of Diverted Tokamaks. G. M. Staebler and F. L. Hinton.

2D17 TF-Rippled Equilibrium for ITER. L. M. Hively, S. P. Hirshman, J. A. Rome.

2D18 Coil Realization for Low Aspect Ratio Stellarators. James A. Rome, Ronald H. Fowler, Peter K. Merkel.

2D19 Physics Scaling of D-T Reactor Plasmas. R. J. Bickerton.

2D20 Natural Elongation,0an Old Fashioned MHD Problem. S. P. Hakkarainen, R. Betti, J. P. Freidberg, R. Gormley.

2D21 Decay of Long Time Correlations in Hamiltonian Systems. Hyung-tae Kook and James D. Meiss.

2D22 Equilibrium of a Plasma in the Fluid and Kinetic Theory. Wann-Quan Li and Swadesh M. Mahajan.

2D23 ECH Deposition Profiles in TJ-II With a Non-Maxwellian Electron Tail. C. Alejaldre and F. Castejon.

2D24 Transport of High Power 140 and 250 ghz Radiation from an FEL Waveguide up to and Through the Entrance of the Microwave Tokamak Experiment. J. A. Byers, T. D. Rognlien, B. Stallard, M. Makowksi, T. Samec.

2D25 Particle-in-Cell Simulations of Electron Heating by Upper Hybrid Waves Using the Massively Parallel Processor. C. S. Lin, J. D. Menietti and H. K. Wong.

2D26 Spatial Effects on the Ignition and Burn of Dl-^{3}He Mixtures. L. E. Sugiyama.

2D27 Mercier Stability Criterion with Plasma Flows. S. T. Chun and E. Hameiri.

2D28 Drift-Rippling Theory of Edge Turbulent Transport. D. R. Thayer, P. H. Diamond, B. A. Carreras, J. A. Holmes, J. N. Leboeuf, Ch. P. Ritz and A. J. Wootton.

2D29 Impurity-Driven Drift Waves in the Reversed Field Pinch. Richard A. Gerwin.

2D30 Extension of Fluid Moment Descriptions to Include Kinetic Effects. J. D. Callen and Z. Chang.

2D31 Effects of Particle Transport on Sustained Ignition in the ITER Design. M. H. Redi and S. A. Cohen.

2D32 MHD Fluctuation Level and Transport in Reversed Field Pinch. K. Miyamoto.

2D33 Non-Local 1-D Kinetic Stability of FRC. P. Papanikolaou, H. R. Lewis, and C. K. Choi.

2D34 Access to the Second Stability Regime in the PBX-M Tokamak. S. C. Jardin, M. S. Chance, and M. Okabayashi.

2D35 Fishbones and Sawtooth Stabilisation in the Kinetic Bulk Ion Regime. F. Pegoraro, F. Porcelli, T. J. Schep, B. Coppi and S. Migliuolo.

2D36 DC-Helicity Injection in an RFP. Y. L. Ho.

2D37 Thermally Driven Magnetic Edge Turbulence. F. T. Plänt, G. Craddock, and P. W. Terry.

2D38 Simulation of Plasma Flow in a Non-Uniform Magnetic Field. Makarem Hussein and G. A. Emmert.

WEDNESDAY MORNING 9:00 - 1:00pm

3C POSTER SESSION
Gunter Terrace
9:00 - 11:00am

3C1 Collisionless Magnetic Reconnection. K. Sandusky, I. Doxas, W. Horton, and T. Tajima.

3C2 Second Stability Region Studies for PBXM and TFTR. M. W. Phillips, M. H. Hughes, A. M. M. Todd.

3C3 The Relationship Between Local Transport and Global Confinement. W. A. Houlberg, S. E. Attenberger, H. C. Howe, and N. A. Uckan.

3C4 A General Asymptotic Solution for Large Aspect Ratio High Beta Equilibrium. S. C. Cowley, R. S. Kelly, R. M. Kulsrud, and P. K. Kaw.

3C5 Ray Tracing of Mode-Converted Ion-Bernstein Waves in Toroidal Plasmas. A. K. Ram and A. Bers.

3C6 The Effect of Poloidal Field on Ion-Ion Hybrid Resonance in Large Tokamaks. Kaya Imre, H. Weitzner, D. C. Stevens, and D. B. Batchelor.

3C7 Comparison of Equilibrium Plasma Profiles with Theory Based on the Gauss-Hertz Principle. Richard L. Moore.

3C8 Two Timescale Analysis of a Coherent Current Filament in the Presence of Magnetic Microturbulence. N. Mattor, P. W. Terry, and J. D. Callen.

3C9 Error Field Behavior and the Parallel Current Profile in an RFP. K. L. Sidikman, J. D. Callen, R. A. Nebel.

3C10 A Theory of Collisionless Trapped Electron Mode Turbulence. F. Y. Gang, P. H. Diamond, H. Biglari, and M. N. Rosenbluth.

3C11 A Free Boundary Algorithm for the BETAS Code. Octavio Betancourt.

3C12 Global Energy Confinement Degradation Due to Mirnov Oscillations and Other Macroscopic Phenomena in Tokamaks. Z. Chang and J. D. Callen.

3C13 A Self-Consistent Wave-Kinetic Formulation of Wave-Plasma Interactions. E. R. Tracy, A. H. Boozer and A. J. Neil.

3C14 Three Dimensional Gyrokinetic Plasma Simulation Models for the Study of Low Frequency Microinstabilities. R. D. Sydora, H. Naitou, W. W. Lee, J. M. Dawson and T. S. Hahm.

3C15 Strong Electron Heating and Stimulated Brillouin Backscatter in FEL-Heated Magnetized Plasma. Bruce I. Cohen and Thomas D. Rognlien.

3C16 Dynamics of Fluid-Polymer Solutions: An Analogue of Magnetohydrodynamic Turbulence. P. H. Diamond, D. R. Nelson.

3C17 Temperature Gradient Driven Instabilities in FRCS. R. Farengo, P. N. Guzdar and Y. C. Lee.

3C18 Stability Window for Internal Global Modes in Igniting Plasmas. B. Coppi, P. Detragiache, and S. Migliuolo, F. Pegoraro, and F. Porcelli.

3C19 3-D Modeling, Simulation and Evaluation of ICRF Antennas. W. Grossmann, K. Ko, A. Drobot, R. Majeski, T. Tanaka, N. Hershkowitz.

3C20 Dissipative Trapped Electron Modes in Lamda = 2 Torsatrons. N. Dominguez, K. C. Shaing, and B. A. Carreras.

3C21 Finite Mean Free Path Corections to Parallel Heat Flow in Divertors. T. D. Rognlien.

3C22 Particle Simulations of Finite Beta Resistive g-Mode in Sheared Slab Geometry. J. H. Han and J.-N. Leboeuf.

3C23 A Knowledge Engineering Based Expert System Interface for an NMFECC Plasma Physics Tool Box Utility. G. D. Kerbel and M. G. McCoy.

3C24 Coupled Energy and Particle Transport Near a Separatrix. F. L. Hinton.

3C25 Effects of Neutral Injection and Neutral Recycling on Tokamak Confinement. H. Okuda, C. Z. Cheng, and S. Hiroe.

3C26 Magnetohydrodynamics and Nonlocal Resistivity Combined in Reversed Field Pinch Profile Sustainment. R. W. Moses.

3C27 Nonlinear Core Plasma Response to RF Power Absorption and Transport in Tokamaks. M. D. Carter, D. B. Batchelor, E. F. Jaeger.

3C28 Unified Theory of Ballooning Instabilities and Temperature Gradient Driven Trapped Ion Modes. X. Q. Xu, M. N. Rosenbluth.

3C29 A New Method to Measure q-Profiles Using a Diagnostic Neutral Beam. P. M. Valanju.

3C30 Transport of Modeling PBXM. M. H. Hughes, M. W. Phillips and A. M. M. Todd.

3C31 Test for Rippling Mode Transport at the Edge of TFTR. R. J. Goldston, E. Fredrickson, M. C. Zarnstorff, C. E. Bush, T. S. Hahm, D. K. Mansfield, H. Park, A. T. Ramsey, J. Schivell, G. Taylor.

3C32 Pulse Length and Ignition Probability Studies for the Compact Ignition Tokamak. D. P. Stotler, N. Pomphrey, R. J. Goldston, and M. G. Bell.

3C33 On the Role of Electromagnetic Microturbulence in Ohm's Law and Dissipative Fluid Instabilities. H. Biglari and P. H. Diamond.

3C34 The Effect of Neutral Beam-Driven Currents on the Nonlinear Dynamics of Magnetic Islands. C. Hegna and A. Bhattacharjee.

3C35 ICRF Full Wave Field Solutions and Absorption for D-T and D-He Scenarios. J. Scharer and R. Sund.

3C36 Kinetic Modification of Nonlinear Toroidal Eta-i Mode. B. G. Hong and W. Horton.

3C37 Helical Coil Driven Sawteeth. M. E. Kress and K. S. Riedel.

3C38 Influence of Trapped-Electron-Pressure-Gradient-Driven Turbulence on Supershot Confinement. T. S. Hahm and W. M. Tang.

3D POSTER SESSION
Gunter Terrace
11:00 - 1:00pm

3D1 Consequences of n=1 Toroidal Misalignments Between Coil and Inner Wall Limiters. B. G. Lane.

3D2 Considerations of Electron Dynamics in a Gyrokinetic Plasma. W. W. Lee, T. S. Hahm, and J. V. W. Reynders.

3D3 The Bootstrap Current in Stellarators. Allen H. Boozer, Henry Gardner.

3D4 Self-Consistent Collision Code for Beam Tracking. T. Tajima and J. Koga.

3D5 Inverse Cascades in 2D Compressible Turbulence. J. P. Dahlburg, R. B. Dahlburg, J. H. Gardner and J. M. Picone.

3D6 Analytic Model for Electron Cyclotron Heating Profiles. R. C. Goldfinger, D. B. Batchelor.

3D7 Lower Hybrid Wave Propagation and Absorption in a Tokamak. D. C. Stevens and H. Weitzner.

3D8 Singular Adiabatic Approximation to Low-Resistivity Magnetofluid Dynamics. Albert A. Blank and Michael E. Kress.

3D9 Lower-Hybrid Wave Penetration with GW Pulsed Power in ITER. R. H. Cohen, T. D. Rognlien, P. T. Bonoli and M. Porkolab.

3D10 Turbulent Transport in Tokamaks Due to Drift-Alfven Fluctuations. A. A. Thoul, P. L. Similon and R. N. Sudan.

3D11 Comparison of Ballooning Mode Stability Properties of Tokamaks with Different Cross Sections and the Same Poloidal Flux. J. L. Johnson, J. Manickam, and A. Miller.

3D12 Dependence of Faraday Shield Sputtering Rate on the Local Plasma Density. M. J. Gerver, D. A. D'Ippolito and J. R. Myra.

3D13 Radial Electric Field and Enhanced Confinement Regimes in Tokamaks and Stellarators. K. C. Shaing, W. A. Houlberg, G. S. Lee, B. A. Carreras, and E. C. Crume, Jr.

3D14 The "Dynamic Layer Model" for L- to H-mode Transition. Y.-T. Lau

3D15 Heat Pulse Propagation with Drift-Wave-Turbulence Models for Thermal Conductivity. F. W. Perkins.

3D16 Alpha Particle Microinstabilities and Stabilization of MHD Modes. C. Litwin.

3D17 Numerical Simulations of the Ion Pressure Gradient Driven Turbulence. S. Hamaguchi and W. Horton.

3D18 Study of Limiter/Separatrix Effects on Tau-p. Emilia R. Solano.

3D19 Stability Analysis of Free Boundary Modes for ATF. F. Bauer and P. Garabedian.

3D20 Studies of Axisymmetric Modes in Tokamak Plasmas with Active and Passive Feedback. D. J. Ward, S. C. Jardin, C. Z. Cheng.

3D21 Analytic Studies of ICRF Heating. C. Chow, V. Fuchs, and A. Bers.

3D22 Investigation into Resistive Drift Ballooning Modes in a Poloidal Divertor Tokamak. E. Uchimoto and H. R. Strauss.

3D23 Electron Cyclotron Wave Propagation and Transport Studies in the Compact Ignition Tokamak. R. C. Englade, P. T. Bonoli, R. C. Myer, M. Porkolab, G. R. Smith, A. H. Kritz.

3D24 Modeling of Fluctuations in the Edge of the Text Tokamak. D. K. Lee, B. A. Carreras, R. H. Fowler, J. A. Holmes, J. N. Leboeuf, Ch. P. Ritz, A. J. Wootton, D. R. Thayer, P. H. Diamond.

3D25 Access to Second Stability in ATF. B. A. Carreras, N. Dominguez, J. N. Leboeuf, V. E. Lynch, L. A. Charlton, J. H. Harris, M. Murakami, J. D. Bell, V. K. Paré, J. L. Dunlap.

3D26 Ballooning Beta Threshold for the Second Region of Ideal MHD Stability in Tokamaks. S. A. Sabbagh, M. W. Phillips, G. A. Navratil, and A. A. M. Todd.

3D27 Resistive Tearing Instability with Equilibrium Shear Flow. X. L. Chen and P. J. Morrison.

3D28 Nonlinear Effect of Waves in the Ion Cyclotron Range of Frequencies on Ion Temperature Gradient Drift Modes. J. B. McBride.

3D29 Calculation of Saturated Tearing Modes Using the PIES Equilibrium Code. N. Pomphrey, A. H. Reiman and D. Monticello.

3D30 Toroidal Field in Field-Reversed Configurations During Translation. A. G. Sgro.

3D31 Nonlinear Tearing Modes in the Reversed Field Pinch. Guthrie Miller.

3D32 Second-Stability MHD Equilibrium Candidates for a Reactor. Kenneth Evans, Jr. and David A. Ehst.

3D33 Scattering From Magnetic Fluctuations in Tokamaks. Linda Vahala, George Vahala, Dieter Sigmar.

3D34 Three-Dimensional Kinematic Reconnection in the Presence of Field Nulls and Closed Field Lines. J. M. Finn and Y.-T. Lau.

3D35 Revised Stability for the Z-pinch, and Prediction of a Class of Magnetostatic Plasma Oscillations. N. A. Salingaros.

3D36 The Effect of the Ideal Kink Mode on Sawtooth Behavior. R. E. Denton.

3D37 New Particle Algorithms for Fusion Applications. M. Kotschenreuther.

Experimental Status of the High-Beta, Second Stability Regime in Tokamaks and Stellerators

ATF Experimental Group
Oak Ridge National Laboratory

DIII-D Experimental Group
General Atomics

HBT Experimental Group
Plasma Physics Laboratory
Columbia University

PBX-M Experimental Group
Plasma Physics Laboratory
Princeton University

Versator II Experimental Group
Plasma Fusion Center
Massachusetts Institute of Technology

As has been predicted theoretically, a second stability regime exists for tokamaks and stellerators allowing high-beta operation up to each device's equilibrium limit that is free of ideal MHD ballooning and interchange instabilities. For the tokamak, with positive global shear, increasing beta first decreases and then increases the local shear in the tokamak's bad curvature region, and this at first destabilizes and then restabilizes ideal ballooning modes. The region of ballooning instability can be avoided all together by several techniques such as deepening the magnetic well by increasing the central safety factor, reversing the local shear at low-β with shaping, or using a combination of both techniques. For the stellerator, with negative shear, ideal interchange modes are the dominant instability and can be stabilized by the magnetic well produced by an outward axis shift. ATF was designed to access second stability in this way. This shift can result from either an applied vertical field or increasing beta. Since the tokamak requires a toroidal current, a high-beta tokamak must also stabilize low-n external kink instabilities represented by the well-known limit $\langle\beta\rangle/(I/aB) < 2$ to 3.5. Although these external modes are theoretically predicted to be stable when the plasma is surrounded by a close-fitting conducting shell, if not stabilized, they present an equally, if not more important, barrier to achieving reactor relevant (*i.e.* high toroidal beta) plasmas in the second regime.

Several experiments have recently attempted to reach the second stability regime. The DIII-D and the Versator II tokamaks have operated at high edge safety factors ($q_a \geq 30$) and sustained high central safety factors ($6 > q_0 > 1$) using either neutral-beam or lower hybrid current drive. Both experiments achieved long-lived equilibria with high poloidal beta, $\beta_p \geq R/a$. Reconstruction of the equilibrium using either external poloidal field measurements (in DIII-D) or hard x-ray measurements of the rf-driven current-carrying electrons (in Versator II) permitted numerical stability analyses of the experiments. These suggest that these plasmas may be near or beyond the transition to the second stability region. In the ATF stellerator with peaked pressure profiles the Shafranov shift is large and allows access to the second stable regime at low $\beta_0 < 1.3\%$; the experiment has already achieved $\beta_0 = 3\%$. Low mode number poloidal magnetic field fluctuations increase with β and then saturate and decrease for $\beta_0 > 1.5\%$.

In tokamak discharges, second stability regime operation with high poloidal beta only implies high toroidal beta when I/aB is large (since $\langle\beta\rangle \sim 4\beta_p(I/aB)^2$), and this destabilizes external modes. These low-n modes have been seen to limit operation in the DIII-D and PBX tokamaks. In the short-pulsed HBT tokamak, the internal magnetic structure of these modes have been compared with the predictions of ideal MHD theory. The first experiments designed to test the effectiveness of a close-fitting conducting shell to slow the growth of the external pressure-driven kinks have been initiated with the bean-shaped PBX-M tokamak.

In this review, we propose to summarize these experimental results, briefly describe plans for future experiments, and indicate the significant progress that has been made in our understanding of the routes to second stability.

Information Content of Transient Synchrotron Radiation in Tokamaks*

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Brief heating of superthermal tokamak electrons produces a transient, synchrotron radiation signal, in frequency-time space, with impressive informative potential on plasma parameters. The two-dimensional radiation pattern is sensitive in different ways to different parameters, so that important parameters are roughly *orthogonal*; *i.e.*, remarkably, they can be inferred almost independently. It may be possible to infer, for example, the dc toroidal electric field in the tokamak interior, which is not available by other means, and this inference is not significantly affected by uncertainty regarding, say, the density, n, or the ion charge state, Z_{eff}.

We exploit here several fortuitous circumstances: First, we exploit a separation of time-scales $1/\omega \ll \tau_{\text{det}} \ll \tau_c \ll \tau_{\text{par}} \ll \tau_{\text{exp}}$. That there are many detector observations, τ_{det}, in a slowing down time, τ_c, can multiply by $10^2 - 10^3$ the amount of processible information in a non-transient analysis. Second, the dynamics of the perturbed high-velocity, weakly-relativistic electrons is an entirely linear problem, dominated by coulomb collisions and the dc electric field, with energy diffusion ignorable. Therefore, a Green's function for the radiation response can be defined, independent of plasma temperature; and, very luckily, a fully relativistic analytic solution can be obtained in the limit of small dc electric field. The Green's function is used to consider efficiently many different initial conditions for the incremental distribution function.

Third, our analytic theory is bolstered by several scale-invariant transformations of the radiation response $R(\omega, t)$. Having solved for $R(\omega, t; n, B, E, Q, Z_{\text{eff}}, \theta) = R_0 + E\,R_1$, where Q measures the perturbation amplitude and θ is the observation angle, we also have

$$R(\omega, t; \alpha B) = \alpha R(\omega/\alpha, t; B), \qquad R(\omega, t; \beta Q) = \beta R(\omega, t; Q),$$

$$R(\omega, t; \gamma n) = R_0(\omega, t/\gamma; n) + \gamma^{-1} E\, R_1(\omega, t/\gamma; n).$$

In this purposefully *constrained* problem, a great deal of data informs on but a few choice parameters; the powerful analytic tools make feasible a numerical analysis of data that would otherwise be unthinkable. Essentially all competing sets of plasma parameters that might possibly explain the data can be considered. A model for noise that accounts for either experimental or theoretical uncertainties can be used to simulate data numerically, so that rigorous estimates can be made of the informative worth of data prior to obtaining it. The statistical approach suggested here provides also for utilizing any information available from other sources.

We find that even in the presence of considerable noise, a variety of plasma parameters remains distinguishable, with profile information, using a relatively modest diagnostic system. The diagnostic system includes both the brief, probing rf signal that leads to the incremental synchrotron signal, and an array of frequency detectors with submillisecond time resolution. The information thus obtainable is novel, reliable, and likely quite useful.

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Theory of Fast Wave Current Drive for Tokamak Plasmas

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General Atomics
San Diego, California

Steady state current drive is essential for commercially attractive tokamak reactors or test reactors such as ITER. Radio frequency current drive schemes appear promising in this respect. However, lower hybrid current drive (LHCD) suffers from inadequate wave penetration due to excessive electron Landau damping, while the CW-rf technology is not ready in the near future for electron cyclotron current drive (ECCD). Fast wave current drive (FWCD) has the advantage of economically attractive and ready technology, and good current drive efficiency (comparable to LHCD), but without the penetration problem of the latter. While FWCD at low frequencies (Alfvén frequency range) has been studied [1], the general theory of FWCD at frequencies ranging from below the ion cyclotron frequency to the range of lower hybrid frequency is not well developed. In this paper, we present such a theory. The accessibility and competitive absorption mechanisms are estimated. From these considerations, it follows that there are two bands of frequencies which are attractive for reactor applications, one in the fundamental ion cyclotron range and the other at higher harmonics below the lower hybrid frequency. To quantify current drive efficiency including toroidal effects, a quasilinear operator for electron diffusion in velocity space which is consistent with the linear damping of fast waves is derived. The bounce-averaged Fokker-Planck equation is solved analytically for a model collision operator which conserves momentum. With the use of a simple form factor, the results are shown to be in good agreement with numerical solutions of a standard 2-D bounce-averaged Fokker-Planck code CQL [2] in the Landau limit. Current drive efficiencies are calculated for various parameters. The continuous transition from the low frequency Alfvén limit to the high frequency Landau limit is demonstrated. In reactor-like parameters, the current drive figure of merit $\eta_{\mathrm{CD}} \equiv nIR/P$ is shown to reach around 0.4 to 0.5. It is shown that DIII–D is a device in which FWCD can be unambiguously tested. Generalizations of the theory to relativistic electrons will be discussed.

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*Massachusetts Institute of Technology, Cambridge, Massachusetts

[1] N.J. Fisch, C.F.F. Karney, Phys. Fluids **24** (1981) 27.
[2] G.D. Kerbel, M.G. McCoy, Phys. Fluids **28** (1985) 3629.

The Status of Statistical Transport Theory for Plasma Turbulence*

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The modern era of statistical turbulence theory began for fluids with Kraichnan's discovery in 1959 of the direct-interaction approximation (DIA), and for plasmas with Dupree's 1966 resonance-broadening theory. Little that has been done since is not fundamentally indebted to the pioneering work of those individuals.[1]

A fundamental difference in philosophy between the traditional fluid and plasma approaches seems not to be properly appreciated. In the systematic approach pursued by Kraichnan one derives a statistical closure, then determines its limitations, both by general theoretical arguments and, equally importantly, by detailed and rigorous solution of the closure in the absence of any further analytic simplifications. The approach often followed in plasma physics subordinates mathematical rigor to intuition. This is not undesirable in itself, but intuition can be wrong and important examples of this are known. In plasma physics turbulence calculations, the self-consistent loop between physical intuition and the true nonlinear statistical dynamics has often not been closed. Since one role of closures is to make quantitative predictions about transport coefficients, one must ask whether the statistical approximations in common use in plasma physics really provide more predictive power than the methods based on dimensional analysis. The answer is far from clear.

A number of recent developments which bear on these issues will be reviewed in an integrated fashion. These include (1) several detailed critiques of the "clump algorithm"[2]; (2) the development of a large computer code[3] which solves two statistically realizable closures: the DIA, and a Markovian version thereof; and (3) the theory of rigorous bounds on transport.[4] Together, these advances provide a framework, albeit still incomplete and relatively rudimentary, within which more speculative assumptions and approximations can be rationally assessed. Much work remains to be done. At the present time, one does *not* have a useful predictive theory of turbulent plasma transport, although it is conceivable that such a theory will be developed in the future.

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* This work was supported by U.S.D.o.E. Contract No. DE–AC02–76CHO3073.

[1] Many references to early work are given by J. A. Krommes, in *Handbook of Plasma Physics*, edited by A. A. Galeev and R. N. Sudan (North-Holland, Amsterdam, 1984), Vol. II, Chap. 5.5.

[2] J. A. Krommes, *Phys. Fluids* **29**, 2756 (1986); *Phys. Fluids* **31**, 869 (1988).

[3] J. A. Krommes and J. C. Bowman, *Bull. Am. Phys. Soc.* **33**, 2022 (1988); Bowman and Krommes (this meeting).

[4] J. A. Krommes and R. A. Smith, *Ann. Phys.* **177**, 246 (1987); C.–B. Kim and J. A. Krommes, *J. Stat. Phys.* **53**, 1103 (1988).

THEORETICAL STUDIES OF TIGHT ASPECT RATIO TOKAMAKS

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Tight aspect ratio devices (i.e., having aspect ratio $A = R/a < 2$) are receiving increasing attention. The interest in such devices arises partly from the changes expected in the physics behavior at tight aspect ratio, and partly from the possible advantages these, and the near-spherical topology, might give to a tight aspect ratio reactor.

The paper presented will discuss theoretical and computer simulation studies of the experiment "START" now under construction at Culham. Using existing vacuum vessel and power supplies, START hopes to achieve a hot (~200 eV), high current (>100 kA) plasma at aspect ratio as low as A = 1.2. This plasma is made possible by use of a technique of plasma formation at large radius, followed by a major radius compression.

The physics objectives of the experiment are:

1. to verify the equilibrium properties, with a plasma of central temperature ~200 eV;

2. to compare MHD behavior (gross stability, sawtoothing, density and current limits) with that of theory and conventional tokamaks;

3. to study the enhanced ohmic heating and profile shaping due to neo-classical resistivity; and

4. to investigate the confinement properties.

Initial simulation results will be reported of the start-up and compression sequence of the START configuration, together with transport code simulations of the final compressed state. These show that at this very tight aspect ratio, the neo-classical enhancement of Spitzer resistivity can approximately double the ohmic heating. Equilibrium studies have previously demonstrated a large increase in edge safety factor due to toroidicity and shaping effects. This enables large increases in plasma current (and hence a high beta limit) whilst keeping q_a significantly above 2. However, high currents are especially difficult to achieve at tight aspect ratio, and an alternative mode of operation is considered; namely to keep the current relatively low, use the high shear properties to give enhanced stability, and to achieve high beta through second regime operation.

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The Stability of the High Density Z-Pinch

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Fiber-initiated High Density Z-Pinch (HDZP) experiments at LANL, NRL, and Karlsruhe have shown anomalously good stability against modes predicted by ideal MHD and observed on earlier compression pinch experiments. Kink ($m=1$) modes are never observed, and sausage ($m=0$) modes are delayed until late in the discharge. If this anomalous stability can be understood and shown to persist into the higher temperature regimes of experiments now approaching operation, then the HDZP may have important applications in the magnetic fusion energy program. Nonideal effects such as resistivity, viscosity, thermal conductivity, FLR effects, and equilibrium flows may account for the anomalous behavior observed. Two complementary numerical methods have been developed to test this hypothesis. They contain all the effects in Braginskii's equations except electron inertia and separate species temperatures. These equations should be valid up to a few keV.

The first method is to numerically integrate a ninth-order complex system of ODE's for the linear $m=0$ eigenfunctions and growth rates. This is a complicated form of shooting code with a singular boundary at each end of the radial domain, one at the axis of the cylinder and one at the plasma edge where the density vanishes. The behavior at the singular points of these high-order equations has been formulated as a matrix eigenvalue problem and solved with the help of Macsyma. The stiff ODE's are integrated with LSODI, an implicit form of the stiffly stable Gear package. Special decoupling techniques have been used to maintain the numerical independence of solutions obtained from different initial conditions at the plasma edge. Equilibrium profiles are obtained from a realistic 1D Moving Finite Element simulation of the HDZP, fit to cubic splines. Both Nyquist contours and root finding are used to study stability, locate unstable roots, and study eigenfunctions. Extensive graphical techniques have been developed to clarify the stabilizing influence of the many different physical processes.

The second method uses a 3D pseudospectral MHD initial value code which has been modified to include complete fluid terms. This code has in the past made use of a semi-implicit time step which eliminates the timestep constraint imposed by the Courant stability condition on explicit methods while avoiding the need to solve large, sparse linear systems. The new terms impose a much more severe Courant limit, making the need for this technique more extreme, while at the same time preventing the use of certain splitting methods used previously. Wave equations associated with both the Hall effect and the FLR terms have the form of a telegraph equation. The maximum allowed timestep scales as the mesh spacing squared. One cannot afford to compute these terms explicitly for any reasonable timescale. Stability to the FLR terms is achieved through a fully implicit advance requiring the solution of nothing more than a block tridiagonal system with 3x3 blocks.

Both methods will be discussed, and results will be presented. The very different algorithms allow mutual confirmation and provide complementary ways of viewing the problem. Principal results to date indicate that resistivity stabilizes the $m=0$ modes at low temperatures while viscosity stabilizes them at high temperatures. The study clarifies the role of many obscure terms in Braginskii's equations. The techniques developed to treat this problem should also have applications to a complete fluid treatments of singular resistive MHD modes in tokamaks and other toroidal devices.

SOFT AND HARD THRESHOLDS FOR ION TEMPERATURE GRADIENT DRIVEN TRANSPORT*

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The ion temperature gradient instability in its most robust (long wavelength) form is a purely growing, fluid-like mode with a growth rate given by $\gamma \sim k_{\parallel} v_i (\eta_i - \eta_c)^{1/2}$ where v_i is the ion thermal velocity, $\eta_i = d\ell n T_i / d\ell n n$, $k_{\parallel}$ is the parallel wavelength, and η_c is the threshold. The mode becomes unstable when the "negative" compressibility associated with the inward convection of cold ions overcomes the "positive" compressibility associated with parallel motion. This gives rise to a value of $\eta_c = 2$ in a collisionless plasma and $\eta_c = 2/3$ in a collisional plasma where compressional energy is shared among three degrees of freedom. Because the mode frequency is small a residual instability exists in the range $2/3 < \eta_i < 2$ even in a weakly collisional plasma ($\nu_{ii} \ll \omega_{*i}$, where ν_{ii} is the ion collision frequency and ω_* is the diamagnetic drift frequency). The mode has a maximum growth rate of order ν_{ii}. The presence of this mode is revealed by the collisional fluid equations, where valid, as well as the kinetic equations with an appropriate Krook collision operator.

Mixing length arguments show that the maximum diffusivity caused by this mode in a sheared slab for η_i between 2/3 and 2 is of order

$$D_i = h(\eta_i) \nu_{ii} \rho_i^2 (L_s / L_T)^2,$$

where ρ_i is the ion gyroradius, L_s and L_T are the shear and temperature gradient scale sizes, respectively, and h increases monotonically with η, maximizing at a value of order .05 as η approaches 2. For $\eta_i > 2$, the diffusivity increases very rapidly to the previously obtained, large, collisionless value.[1]

Thus, the collisional ion temperature gradient mode is capable of providing a "soft" onset for thermal conduction as η_i increases from 2/3 to 2. Whether this thermal conduction is important requires comparing it with that due to competing instabilities, for example, the finite Larmor radius version of the collisionless ion temperature gradient mode. A mixing length argument for the latter mode yields a diffusivity of the form

$$D_i = g(\eta_i, L_n / L_s) v_i \rho_i^2 / L_T.$$

For η_i in the range $.95 < \eta_i < 2$ and in the limit of weak shear $L_n / L_s \ll 1$ the form factor g is a function of η_i only with an estimated maximum value of .05. Thus, the collisional instability will dominate for $\nu_{ii} > (g/h) v_i L_T / L_s^2$.

1. P. W. Terry, et al., Phys. Fluids **31**, 2920 (1988).

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

Numerical Solutions of Statistical Closures for Anisotropic Terry–Horton Dynamics*

John C. Bowman and John A. Krommes
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A comprehensive analysis of the Terry-Horton drift-wave equations is presented using the code `DIA` that was recently developed to solve the direct-interaction approximation (DIA) and a related Markovian closure.[1] Horton proposed a particular Markovian closure[2] for these equations but was unable to solve it analytically because of the combined difficulties of anisotropy and nonlinearity. To obtain estimates of saturated spectra and transport, he studied a much simplified isotropic approximation. It is useful to compare those relatively crude estimates to detailed, more accurate numerical solutions of a fully anisotropic closure. In the present work this is shown to be feasible.

A realizable, Markovian, anisotropic closure similar to Horton's and closely related to the full DIA is considered. In the absence of linear growth, relaxation to the appropriate nonlinear statistical equilibrium constitutes a nontrivial test of the code. When the system is allowed to be driven out of this equilibrium by the linear term, the code evolves to a fully nonlinear saturated state in the strong turbulence regime. The statistical properties of this state are compared with Horton's direct numerical simulations and with his analytic predictions. The energy spectrum of the fluctuations, measures of anisotropy, nonlinear modal damping rates, and other relevant statistical quantities are presented. The particle diffusion coefficient is calculated and its relation to $D \sim \gamma/k_\perp^2$ is discussed. The full DIA closure is also solved for this problem. Saturated energy spectra are similar to those found with the Markovian closure. The DIA closure also yields correlation and response functions of the steady-state fluctuations.

The techniques by which this computation is made feasible are also discussed. Because closures advance statistical variables that are smooth functions of their arguments, only certain sample modes, nonuniformly spaced, need be integrated explicitly; the effects of intervening modes can be taken into account by geometric weighting factors. The calculation of these weights in two dimensions for a log/linear partition of wave-number magnitude/angle involves evaluation of complicated six-dimensional integrals, which is accomplished by a combination of analytical and numerical techniques.

The present calculations support the conclusion that it is possible to obtain quantitative solutions to complicated anisotropic statistical closures for some situations of practical interest. This raises for the first time the possibility of assessing in detail the validity of various severe approximations that are often made in the interest of analytic progress. Although there remains much work to be done, such analysis is essential for gaining a complete understanding of turbulent transport in plasmas.

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Simulation of Neutral Helium Transport in Flat Vented Divertors and Limiters*

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The transport of neutral helium atoms near divertor or limiter target plates has been studied using a two-dimensional Monte Carlo code. The model includes electron impact ionization and elastic scattering by plasma ions. The thermal and streaming motion of the ions along the magnetic field, which can be at an angle to the target plate, is included. The total and differential elastic scattering cross sections have been calculated classically using an ab initio calculation of the interatomic potential [1]. It is seen that elastic scattering of helium by plasma ions is a significant process below 10 eV. The two-dimensional Monte Carlo code has been used to study helium recycling near a flat, vented target plate [2]. A parametric study is performed to show the dependence of the neutral helium current scattered into the pump duct on the ion temperature, the plasma density and the ion flow velocity. Hence, plasma parameters leading to efficient pumping of the helium can be determined.

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CURRENT-DRIVE BY CIRCULARLY POLARIZED ALFVEN WAVES

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ABSTRACT

Ohkawa has proposed a tokamak current-drive scheme which relies on the injection of circularly polarized MHD waves. We show here that the favorable current-drive efficiency predicted by Ohkawa is not attained because excessive power is dissipated by the fluctuating fields. The ratio of power absorbed by the plasma to the DC Ohmic power required to drive the same current is $P_{\mathrm{absorbed}}/P_{\mathrm{Ohmic}} \approx 4(B_a/b)^2$ where B_a is the static toroidal field strength and b is the strength of the fluctuating field.

RFP Dynamo and Reversal in MHD and Hall MHD

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In this paper, we will report on work related to the RFP dynamo and reversal using MHD with and without Hall and diamagnetic effects. We will present the following results:

I. Single Helicity MHD: We will show that single helicity ($m,n \neq 0$) ohmic states exist with reversed field at all positions on the plasma edge. These states exist with and without finite pressure. These results will be compared with analytic theory based on the helical flux surface average of **E·B.** This theoretical formulation shows the possibility of full reversal in single helicity and shows the influence of Pfirsch-Schluter currents when pressure is included.

II. Hall Effect "Dynamo": We will demonstrate that under conditions of high viscosity, the RFP relaxation mechanism emerges from the Hall effect rather than the standard MHD **vxB** nonlinearity. This also results in a substantial shift in the spectrum.

III. Resistive Wall Instabilities: Inclusion of Hall and Diamagnetic effects can also remove m=0 resisitive wall modes under conditions of low viscosity. Surprisingly, the m=0 mode is diminished more with a resistive wall than with an ideal one.

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SPECTRA OF INTERMITTENT MAGNETIC TURBULENCE

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We calculate the magnetic energy spectrum of intermittent 2-D magnetic structures surrounded by cascading turbulence. Motivation is provided by the appearance of current sheets (islands[1]) and filaments[2] in simulations of 2-D MHD turbulence. Similar calculations have been performed for spiral vortex structures in 2-D Navier Stokes turbulence[3].

Two models are used for the coherent structures. The first model is a sheet/island model. The second is a force-free current filament. By comparing these spectra with homogeneous turbulence and discontinuous current sheets one can then connect the spectrum with the topology of the turbulence.

We also discuss the problems with relying only on the second moment (energy spectra) as indicative of structures, and outline a numerical experiment for testing how changes in spectral steepness affect the appearance of the structure. Last, extensions of this 2-D MHD result to a 3-D MHD are discussed. Relations to constrained relaxation such as in an RFP are considered.

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SHERWOOD THEORY MEETING 1989

The Rayleigh-Taylor Instability in a Homogeneously Expanding Plasma*

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We study the Rayleigh-Taylor instability in a static metric and in an expanding metric and compare the results. The latter problem is important, for example, in the Z-pinch configuration of the muon-catalyzed fusion reactor,[1] in which each fuel rod is expanding away from all others. In order to carry out this analysis, we develop an MHD code with an expanding (or general relativistic) metric. The code evolves the complete set of nonlinear, two-dimensional MHD equations. First, we examine the static metric case with a Rayleigh-Taylor instability in a plasma with a sharp, localized gradient in density, pressure, and magnetic field magnitude. Many qualitative features of the Rayleigh-Taylor instability for sharp boundaries between fluids of different densities are reproduced well, such as finger-like projections extending from the dense plasma into the thin plasma and initial exponential growth of the Rayleigh-Taylor perturbation followed by slower growth in the later nonlinear evolution of the instability. The initial growth rate of the instability is within a factor of ~ 2 of the analytical growth rate for a sharp boundary instability. The results of the expanding metric case will be reported.

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ALPHA PARTICLE CONFINEMENT IN TOKAMAKS*

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An assessment of diffusive tokamak transport mechanisms of concern for alpha particles indicates that the "stochastic regime" is the only one which appears to pose a real danger for adequate alpha confinement. This fact, in conjunction with the threshold character of that mechanism, allows one to decide whether an alpha born at a given location will be lost or confined according to a very simple criterion. Implementing this criterion numerically results in a new code for the assessment of alpha confinement, which is orders of magnitude faster than earlier codes used for this purpose. Confinement of alpha particles on ITER and other tokamaks is analyzed. For most devices, although the total energy loss due to alphas is not too important, the wall loading near the midplane can be serious. Induced alpha loss during sawtooth oscillations is also discussed.

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RESISTIVE HELICAL MHD STATES WITH FLOW

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The induction equation $\partial \mathrm{B}/\partial t = \nabla \times (\mathrm{v} \times \mathrm{B} - \eta \mathrm{j})$ shows that any steady-state (or time-averaged) resistive MHD configuration must have a flow velocity v. The only exception is the trivial state $\nabla \times (\eta \mathbf{j}) = 0$. We construct, analytically and explicitly, time-independent resistive MHD states in a periodic cylinder in the presence of an axial electric field. The solution bifurcates at a rather low value of the current. One solution is axisymmetric with $\mathbf{v} = 0$, while the other is a combination of an axisymmetric, zero-flow component and a smaller helical component with flow. The non-axisymmetric state has a *lower* total dissipation rate than the axisymmetric one, for a given driving electric field strength. According to the principle of minimum energy dissipation rate,[1] previously applied to the RFP under the assumption $\mathbf{v} = 0$, this strongly suggests the plasma may prefer the non-axisymmetric state when given the choice, with or without the presence of turbulence-inducing instabilities. The end product of a turbulent relaxation process may equally well be a non-axisymmetric helical equilibrium with flow; existing measurements seem consistent with such a possibility.

Persistent, *low-mode-number*, helical states with vortical flow have emerged from a long series[2] of 3D simulations: Strauss approximation and full MHD; driven and undriven; with and without temperature variation. It is possible to begin to doubt the relevance of ideal, axisymmetric, zero-flow equilibria as a conceptual starting-point for fusion calculations. In mid-19th century hydrodynamics, dissipative terms were erroneously neglected for decades as "small," before it was realized that they could still alter, in fundamental ways, even the basic laminar states.

$\partial \mathrm{B}/\partial t$ is the sum of only two terms: one diffusive (which wipes out gradients) and one depending upon $\mathbf{v}$. Only through v can interior current profiles be set up or maintained which are other than curl free, according to MHD.

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Three-Dimensional Global Simulation of Electron Drift Mode Turbulence

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A 3D (m,n,r) code is used to study the scaling electron drift mode turbulence with respect to shear length (L_s) and gyroradius (ρ_s). A simple $i\delta$ model for the linear nonadiabatic electron response is used $[\widetilde{n}/n = e\widetilde{\phi}/T_e(1-i\delta)$ with $\delta = k_\theta\rho_s \cdot \delta_0]$. For cold ion cases, only ion continuity equation for $\widetilde{n}$ (or $\widetilde{\phi}$) and the ion parallel momentum equation are advanced in time. Ion Landau damping is physically modeled as a parallel viscosity, but an artificial cross-field viscous damping $[\gamma_d \propto \mu_x k_x^2\rho_s^2]$ must be added. Multiple helicity sheared-slab simulations well above threshold are tested against the linear mixing length scaling rules: $\widetilde{n}/n \propto 1/k_x L_n$ with the mixing length proportional to the linear mode widths $k_x^{-1} \propto \rho_s(L_s/L_n)^{1/2}$ where $L_s = Rq/\widehat{s}$ with $\widehat{s} = d\ell nq/d\ell nr$; and the $\widetilde{E}\times B_0$ diffusivity $D \propto \gamma/k_x^2 \propto \delta_0(k_\theta\rho_s)^2(L_s/L_n)\rho_s^2 c_s/L_n$. $[L_n^{-1} = -d\ell nn/dr$, $\rho_s = c_s/\Omega_i$, $c_s = (T_e/M_i)^{1/2}$, $\Omega = eB/mc.]$ $k_\theta\rho_s$ is explicitly independent of ρ_s as expected and also independent of L_s. $\widetilde{n}/n$ and measured radial correlation lengths k_x^{-1} scale with $\rho_s L_s^{1/2}$ and $D \propto \rho_s^2 L_s$ for variations on ρ_s and L_s through a change of R. However, preliminary results show $\widetilde{n}/n$ and D weakly dependent on $\widehat{s}$ which rescales the distance between singular surfaces $\Delta = 1/k_\theta\widehat{s}$ as well as L_s, *i.e.*, there is deviation from mixing lengths scaled to linear mode widths. Transport appears to depend only on the driving strengths within an ion Landau damping distance, *i.e.*, there is no strong evidence for nonlocal convective effects. Subcritical transport is very weak in this model. The model can be extended to include hot ion effects such as FLR and stronger shear damping by including an additional equation for adiabatic evolution of ion pressure perturbations. Some examples of hot ion electron drift mode turbulence and slab ion temperature gradient (η_i) mode turbulence are also presented.

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A Simple Method for Calculation of Magnetic Island Widths*

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One goal of codes for designing helical vacuum magnetic fields is the elimination of islands. Since practical constraints may preclude the complete elimination of islands, one must be able to calculate island widths to determine whether a given design is acceptable. Calculation of island widths is also necessary for comparisons of calculations with experimentally observed islands due to, e.g., error fields.

Determination of island widths using standard methods is computationally intensive. Standard methods require the generation of puncture plots with sufficient detail to find orbits outside but close to the island boundary as well as inside but close to the island boundary. We have developed a new simple method of calculating the island width. This method uses only information obtained from integrating along the closed field line at the center of the island.

Fixed points (the intersection of the closed field line and the surface of section) are found numerically via Newton's method. The linearized motion (or tangent map), which describes the map near the fixed point, is obtained by integrating the transverse gradients of the magnetic field. The trace of the tangent map determines the eigenvalues. Complex eigenvalues imply that the fixed point is elliptical, and the phase of these eigenvalues determines the rotation rate of nearby orbits about the island center. In the small-island approximation, this rotation rate depends on the island width and the local shear. The off-diagonal elements of the tangent map, suitably averaged over the iterates of the fixed point, give the shear of the field lines. Thus, from the full matrix we are able to calculate the island width.

This method of calculation has been implemented in the stellarator optimization code, IFS (Integrable-Field Stellarator). Results for the busswork islands of ATF will be presented.

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Dipole Magnetic Field for an Advanced Fuel Reactor

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ABSTRACT

A dipole magnetic field configuration is suitable for a $D-H_e^3$ advanced fuel reactor because

1. the simplicity and cost effectiveness of the magnetic geometry
2. expected stable confinement of a high $\beta(\geq 1)$ plasma
3. absence of anomalous diffusion due to breakdown of ψ and J invariants for a reasonable plasma profile, i.e., dlnp/dlnr ≥ -6, and
4. possibility of direct conversion.

Theoretical accounts for these merits and possible design example of the reactor will be presented.

EFFECTS OF A TOROIDAL MAGNETIC FIELD ON THE NONLINEAR EVOLUTION OF THE INTERNAL TILT MODE IN AN FRC

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The internal tilt mode (ITM) of an FRC is predicted to be unstable by both MHD and kinetic theory; however, there is no unambiguous experimental evidence for this instability. We have been using a 3D semi-implicit, resistive MHD code to study the instability, and the effects of various terms that are normally neglected. The effects of several terms including the Hall term, rotation, differential rotation, and field shaping has been described elsewhere[1].

While it is usually assumed that an FRC has no toroidal component to it's magnetic field, internal magnetic probe measurements in a recent experiment have found a significant net toroidal flux contained within a translated FRC[2]. We have investigated the effects of this field on the evolution of the tilt mode. The 3D-MHD code is initialized with an equilibrium that neglects the toroidal field, which is then added as a perturbation. It is found that the addition of a toroidal field with a peak magnitude of less than half that of the external field can significantly delay the onset of the instability. The structure of the mode is also found to differ dramatically from cases with no toroidal magnetic field. No net toroidal flux is expected to exist in non-translated FRC's that are formed symmetrically; however, formation calculations that include the Hall term[3] predict equal and opposite toroidal fields to be generated in each end. This field structure has no net helicity and does not represent an equilibrium since the field can decay through the propagation and viscous damping of torsional Alfven waves. The effect of this phenomena on the ITM is also being investigated.

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Simulation of the ion cyclotron emission in the JET Tokamak

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we have developed 2 and 3-d computer models with kinetic ions and massless fluid electrons. Those codes have been rigorously tested against the linear analytic theory. We generalized the code 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. We have applied this model to the neutral beam heating of a fusion plasma, in particular to the study of waves and instabilities. Remarkably we observed incresed fluctuation levels of the peaks of the power spectra at the various integral as well as half integral ion cyclotron harmonics for all the wave modes upon the beam injection. Furthermore we also simulated the case in which a very small fraction of the plasma was comprised of the fusion products and also observed sharp power spectra peaks at the cyclotron as well as 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 ion cyclotron frequencies were observed upon injection of neutral beams and also after fusion products were produced. Thus, these results could well establish some theoretical understanding of the experimentally observed phenomenon.

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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 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. The toroidal current apparently results from a dynamo action ($\eta\vec{J} = \vec{v}\times\vec{B}$) due to the net radial flow of plasma; however, at the magnetic axis, this simple mechanism does not generate current. The bootstrap theory[2,3] therefore requires, as a constant boundary condition, an independently generated "seed current" on axis, which is spatially amplified by the dynamo mechanism to give rise to current over the entire cross-section of the plasma. One conventionally assumes that the seed current must be externally driven, but CCT experiments suggest that it may arise spontaneously, by some other mechanism which is not yet understood. To study this effect, 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, allow for comparison with theoretical and experimental results. In a reactor, the alpha particle heating combined with central fueling and efficient particle removal at the wall could establish a plasma flow in which this transport driven current would supply a large fraction of the required toroidal current.

Research supported by DOE.

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Two-Fluid Theory for Collisional Presheath with Viscosity*

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The collisional presheath region is modelled by fluidlike moment equations derived from kinetic theory in order to investigate the problem of a collisional plasma flowing into a perfectly absorbing wall. Previous work has been based primarily on the collisional Braginskii equations[1] or collisionless kinetic theory.[2] The determination of the electron distribution function is shown to be a Pastukhov type problem.[3] Also, a kinetic theory is required to determine the ion viscous stress tensor in the presheath region because the collisional mean free path is comparable to the characteristic scale length there. It is shown that the determination of the ion distribution function can be reduced to a Wiener-Hopf boundary layer type problem.[4] The viscous force deduced from this solution is dominant in the presheath region closest to the sheath region. The resultant semi-fluid model derived from including kinetic effects in the viscous force is discussed. Also, numerical solution of the 7 coupled differential equations, which consist of 6 moment equations for ions and electrons and Poisson's equation, will be presented.

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TRANSPORT COEFFICIENTS FOR THE PLASMA THERMAL ENERGY AND EMPIRICAL SCALING "LAWS"*

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Advanced experiments on the confinement properties of plasmas in regimes of thermonuclear interest suggest that a transport theory that could explain them should:

→ reproduce the observed temperature profiles,

→ be related to the theory of a collective mode that can be excited in the relevant physical regimes,

→ lead to a scaling to the energy replacement time τ_E that is compatible with those obtained by surveys of a relatively wide variety of experiments.

The theoretical model presented in this paper: i) is based on the properties of the so-called "ubiquitous" trapped particle mode [1], and derived by using similar arguments to those given in Ref. 2 for the so-called η_i-mode; ii) it produces transport of both the electron and the ion thermal energy, iii) it generates to temperature profiles that are consistent [3] with those experimentally observed and are nearly independent of the heating source; iv) it leads to the following scaling for τ_E

$$\tau_E \simeq C_E \left(\frac{\bar{n}_e \kappa}{W_h}\right)^{3/5} \left(\frac{I_p}{\alpha_T}\right)^{4/5} a\ R^{6/5}\ (q\bar{A}_i)^{2/5}\ /(Z_{eff})^{1/5} (\mathrm{ms,MA,m,MW}),$$

and $C_E \simeq 1.75\times10^{-13}$. This scaling, with the value of C_E adapted to reproduce the values of τ_E in experiments where a significant degradation of τ_E as a function of the total heating power W_h is observed (the so-called L-mode), is derived following a procedure indicated by Perkins [4] and is similar to that already proposed by Lackner and Gottardi [5]. Here $\bar{n}_e$ is the line average electron density in m^{-3}, κ the elongation of the cross-section, I_p the plasma current $\alpha_T \equiv -d\ell n T_e/d\ell n r^2$, $\bar{A}_i$ the mean ion mass number and the remaining symbols are well-known.

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Relativistic Damping of Electron Cyclotron Waves in Anisotropic Plasmas and Its Application

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If a plasma is heated by an intense electron cyclotron wave or by an electron cyclotron wave together with an intense lower hybrid wave or an intense fast wave, the electron distribution becomes non-Maxwellian and wave damping in such a plasma is no longer described by theories based on a Maxwellian distribution. In order to do a ray tracing study of an electron cyclotron wave in such a plasma, it is convenient to model the electron distribution by an analytical function. In this paper, an electron distribution function is assumed to be in a form

$$f = N \exp\left[-\lambda\gamma + \lambda_{\rm D}\left(1+\beta_{\parallel}^2\right)^{1/2}\right] \quad ,$$

where N is the normalization factor, $\lambda = m_0c^2/T$ for weakly relativistic electrons, $\beta_{\parallel} = p_{\parallel}/m_0c$, and $\gamma = (1+\beta_{\parallel}^2+\beta_{\perp}^2)^{1/2}$. $\lambda_{\rm D}$ is the parameter to be chosen for the anisotropy and should be less than λ. A dispersion relation derived for the distribution has been solved numerically for both electromagnetic modes. As expected, the results indicate that larger $T_{\parallel}$ enhances absorption of both modes and larger $T_{\perp}$ quenches absorption of the ordinary mode. Using this damping computation in a ray tracing study, electron cyclotron current drive efficiencies can be estimated for a plasma pumped by a lower hybrid wave or a fast wave. Discussion also includes inside launch versus outside launch and low power versus high power with respect to the current drive efficiency.

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IDEAL STABILITY OF CYLINDRICAL PLASMA IN THE PRESENCE OF MASS FLOW

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Abstract: The ideal stability of cylindrical plasma with mass flows is investigated using the guiding centre plasma (GCP) model of Grad. For rotating plasmas, the kinetic treatment of the parallel motion in GCP gives significantly different results than fluid models, where the pressures are obtained from equations of state. In particular, GCP removes the resonance with slow magnetoacoustic waves and the loss of stability that results in magnetohydrodynamics (MHD) for near-sonic flows. Because of the strong kinetic damping of the sound waves in an isothermal plasma, the slow waves have little influence on plasma stability in GCP at low β. In the large aspect ratio, low-β tokamak ordering, Alfvénic flows are needed to change the ideal GCP stability significantly. At lowest order in the inverse aspect ratio, flow can be favorable or unfavorable for stability of local modes depending on the profiles, but external kinks are always destabilized by flow if the velocity vanishes at the edge. In three dimensions, the MHD equilibrium problem becomes hyperbolic for *arbitrarily small flows* across the magnetic field, whereas in GCP the equilibrium equation remains elliptic for sub-Alfvénic flows.

PARTICLE AND HEAT PINCH EFFECTS IN COLLISIONLESS TOKAMAK DISCHARGES

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A new fluid description for toroidal temperature gradient driven modes which is not expanded in the ratio ε_n of scale lengths for density L_n and magnetic field, L_B has been derived. In the presence of electron trapping a new collisionless trapped electron mode propagating in the electron drift direction has been found. This mode is essential for obtaining heat pinch effects which may occur for small $\eta = L_n/L_T$, a situation that may prevail locally in connection with pellet fuelling. For $\eta > 1$ and ε_n not too small, particle pinch effects appear due to the toroidal η_i mode. These have been evaluated for a TEXTOR profile and were found to be of the correct magnitude. The overall tendency of the transport is to equilibrate L_n and L_T. The transport has been evaluated with both an analytical model and a fully nonlinear mode coupling code, with good agreement. The fluid model has also been found to be in good agreement with kinetic theory. The effects of compressibility and diamagnetic heat flow are stabilizing and reduce the transport due to the toroidal η_i mode to the correct magnitude. The asymptotic η_i threshold for large ε_n , which gives consistency with the good H-mode confinement, is usually slightly reduced by electron trapping. Analytical expressions for this threshold and the energy and particle diffusion coefficients have been obtained.

Anomalous Diffusion in Stochastic Magnetic Field*

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Anomalous diffusion due to stochasticity in magnetic field is investigated using recent nonlinear dynamical theory. We find escape dynamics from resonances has a universal form in the hyperbolic regime. It is a Markov process for large nonlinearity. The escape rate agrees reasonably well with dynamical theory.

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Disruptions in DIII–D

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Disruptions in DIII–D H–mode discharges are invariably preceded by a sawtooth crash and an ELM. Several models of the effects of the sawtooth crash and ELM on the profiles are investigated numerically for correlations between the disruption and the onset of an n=1 ideal MHD kink. Before the sawtooth crash, the equilibria, reconstructed from shot data, are invariably unstable to an internal kink if q_0 is assumed to be less than unity; this is presumed to drive the sawtooth crash. After the crash, the pressure gradient is redistributed by reducing the central pressure by 20% and increasing the gradient at and near the edge, consistent with experimental observations. The models differ in the way the q profile is modified after the crash. The resulting equilibria are tested for the presence of an ideal n=1 external kink that can then be presumed to cause the disruption. Scenarios for avoiding disruptions will also be discussed.

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A Linearized Resistive MHD Stability Code*

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A stability code (NOAH) is being developed that solves the linearized resistive MHD eigenmode equations for a given axisymmetric toroidal plasma equilibrium with noncircular flux surfaces. The approach being used has already been successfully applied to the linearized *ideal* MHD eigenmode equations in the NOVA code.[1] A specific formulation of the linearized resistive MHD eigenmode equations in toroidal geometry has been chosen on the basis of consistency with the tearing and interchange ordering and accuracy in resolving the continuous spectrum. By choosing a formulation which does not require lower order cancelation in order to resolve the continuous spectrum, the numerical errors caused by "spectral pollution" are avoided. A cubic B-spline finite element method is used to solve the linearized resistive MHD equations everywhere in the plasma, rather than using asymptotic matching between ideal and resistive regions.

Results are presented from a code which implements the cylindrical limit of this formulation and recovers the results of asymptotic and shooting codes which have already been applied to the 1-D problem. Convergence studies performed on an interchange mode in a spheromak-like equilibrium show that modes found with Magnetic Reynold's numbers as high as $S = 10^{15}$ are converged with on the order of only 100 grid points, and agree with asymptotic matching code results.

Results from the 2-D code are also presented. We demonstrate that the 2-D code is able to recover the results from the NOVA code in the ideal limit and the results of other cylindrical codes in the non-ideal cylindrical limit.

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

THE EFFECT OF PARALLEL THERMAL CONDUCTIVITY ON THE STABILITY OF RESISTIVE BALLOONING MODES

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The stability of resistive ballooning modes is studied in the strongly collisional and semicollisional regime using the two fluid Braginskii equations in the cold ion limit. In the resistive MHD limit previous results are recovered and the role of parallel compressibility and perpendicular transport is discussed. When parallel thermal conduction is taken into account, previous results are generalized. Particular emphasis is given to the problem of the boundary conditions to be used in solving the eigenvalue equation.

Finite Beta MHD Effects on Thermal Transport

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I. Long time dissipative MHD simulations have been done of high beta large aspect ratio tokamaks. This gives equilibrium profiles produced by a balance of MHD effects, transport, heat source, and voltage. Dissipation is provided by Spitzer resistivity and perpendicular thermal conduction. Parallel transport is modelled by sound waves. The following results are obtained:

(1) Energy confinement time vs. input power and other parameters — long wavelength electromagnetic resistive ballooning modes cause beta to saturate. Near the beta limit, τ_E varies as a fractional negative power of the heating rate.

(2) Stationary states with profile consistency — the temperature profile peakedness is proportional to the edge safety factor $q(a)$, and the sawtooth inversion radius is inversely proportional to $q(a)$.

(3) Beta limit disruptions — if the heating rate is increased, an $m = 2, n = 1$ mode grows rapidly after a sawtooth, and flattens the temperature profile within the $q = 2$ rational surface. This resembles disruptions seen on DIII-D.

(4) Extensions to bean shaped cross section tokamaks are in progress. This may avoid the MHD β limit.

II. In the extraterrestrial context of the solar corona, ballooning modes may play an important role in thermal transport. This is because presently favored theories of coronal heating — such as Alfven wave resonant absorption — deposit heat in thin layers, which implies large pressure gradients. Classical transport is inadequate to conduct heat across the magnetic field, but ballooning turbulence should be more than sufficient [1].

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The Case for Cold Ions Diffusing Inwards in Tokamaks Too Rapidly to Thermalize*

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Cold ions (n_c) are produced near the wall or separatrix due to gas puffing or recycling. It is argued that they will diffuse inwards too rapidly to thermalize with the outwardly diffusing hot ions (n_h) and will penetrate well into the plasma. Their collision frequency for momentum transfer is large — the dominant part $\nu_{cz} \sim n_z Z^2 T_c^{-3/2}$ — but for energy transfer it is much smaller — $\nu_{ch} \sim n_h T_h^{-3/2}$. The cold ions will be trapped in the electrostatic potential well on a magnetic surface (or in the centrifugal force potential well after rapid acceleration to the toroidal mass velocity, if present) and will be driven inwards by the large parallel friction force $F_{cz} = n_c m_i \nu_{cz} [V_\phi - (E_r/B_\theta)]$ or

$$\widetilde{F}_{cz} = n_c m_i \nu_{cz} [-(n_z'/n_z) + (n_c'/n_c)] \widetilde{\Phi}(\theta)/B_\theta \; .$$

Potential wells due to electrostatic turbulence will increase this rate of inward flow. Many experimental results have a simple explanation with this model, including (a) the increase with density of the in-out density asymmetry driven by the centrifugal force in PDX[1] even though $V_\phi \sim n^{-1}$ (the cold ions add to the centrifugal force, but not to the balancing $\partial p/r\partial\theta$,) (b) the fact that pulsed gas puffing in PLT[2] and TFTR[3] led to rapid increase in central density, but no increase in energy content, (c) the recent improvements in containment — H-mode, pellet injection, supershots and I.O.C. (in Asdex), all of which involve reduced gas puffing or recycling, (in steady state F_{cz} is balanced by an equal and opposite force, F_{hz}, which drives the hot ions out — reducing n_c reduces the outflow of hot ions) and (d) the failure of impurities to accumulate strongly in the center as predicted by neoclassical theory ($\widetilde{F}_{cz}$ drives the impurities out, balancing $\widetilde{F}_{hz}$, which drives them in).

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Effects of Finite Aspect Ratio on High-n Instabilities in Tokamaks*

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The stabilizing effect of the Shafranov shift (resulting from finite pressure gradients) in reducing the "bad curvature" that destabilizes modes like the MHD ballooning mode and the collisionless trapped-electron mode is well known. It is this effect that leads to the so-called "second stability regime" and can cause "drift reversal" for trapped particles. However, even at zero pressure, the modification of the magnetic drifts by decreasing aspect ratio can lead to similar effects (*e.g.*, for very tight aspect ratios of less than two or so). The properties of the magnetic drifts can be quite different from those expected on the basis of large-aspect-ratio expansions. Stability results are presented from a comprehensive electromagnetic kinetic eigenmode code[1] for these instabilities. Different cross-sectional shapes are compared (*i.e.*, circular, "bean"-shaped[2], and "comet"-shaped[3] equilibria). The results indicate that the destabilizing effect of the increased fraction of trapped particles can be offset by the improved magnetic curvature properties of sufficiently low-aspect-ratio devices. Significant reduction of relevant growth rates and the associated anomalous transport are predicted for cases where R/a falls below 1.5. Hence, comparing the transport properties in tokamaks as R/a is varied from the familiar range of 3 or 4 to values as low as 1.3 would be most interesting. Since the confinement in sufficiently collisionless regimes may then exhibit measurable improvement for $R/a \lesssim 1.5$, results of these studies could have considerable implications for the design of future tokamak experiments. Moreover, low-aspect-ratio geometry *together with* the aforementioned second stability finite β effects could lead to optimal confinement scenarios. Since experiments capable of obtaining these very small aspect ratios and finite β have been proposed, study of the high-n stability properties for them is clearly of interest.

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Theory of Weak Ion Temperature Gradient Driven Turbulence in Flat Density Discharges

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In previous work(1) it was shown that in the vicinity of threshold ($\eta_i \sim \eta_{icrit}$) ion temperature gradient turbulence saturates at low fluctuation levels via Compton scattering to long wavelength, stable modes, The 'width' of the weak turbulence regime ($\Delta\eta_i = \eta_i - \eta_{i,c}$ for which $\Delta\omega$ ($\Delta\eta_i$) < ω ($\Delta\eta_i$) was calculated and shown to exhibit parametric dependence different from η_{icrit}. Indeed, it was argued that the value of η_i for which $\Delta\omega = \omega$ is a better indicator of 'threshold' then the linear $\eta_{i,c}$. This argument is based on the prediction that in the weak turbulence regime, transport due to η_i- modes is quite feeble.

In this paper, we extend the previous analysis to the flat density regime.

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Bounded Multi-Scale Particle Simulation: The Sheath Problem

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We are using the multi-scale [1] technique to model bounded systems. Certain bounded systems are a naturally suited for the multi-scale method because the boundary layer (or sheath) that forms at the wall, which is usually a short spatial ($\sim \lambda_{De}$) and time scale ($\sim \omega_{pe}$) structure, can signifi antly effect the bulk plasma behavior. One goal is to undersand the interaction between the bulk plasma and the sheath. If the relevant short time scale physics is local to a few (or one) spatial regions, then one can take advantage of this by advancing particles with variable Δt depending on position, hence reducing computing time. The unmagnetized sheath problem is such a case.

The model is a one dimensional bounded slab with kinetic ions and electrons. We start with a collisionless and unmagnetized system for simplicity. The right boundary is a conducting wall that absorbs all particles that come in contact with it. The left boundary is a symmetry point, where the particles are reflected. We allow a specified initial distribution: $f(x, v, t = 0)$, and a distributed source: $s(x, v, t)$.

To test the numerics of both the multi-scale method and boundary conditions we are using the following test problem: a cutoff Maxwellian distribution for the electrons and fixed (or infinitely massive) ions. The system has an analytic solution, so the run may be started from equilibrium. This gives us a benchmark to compare against and tests the fast time scale electron sheath dynamics. Initial results using variable Δt (with ratio of smallest to largest of 1:32) will be given. In the future, we intend to use the more general model to study time dependent sheath problems, such as a shock front interaction with the boundary.

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Localized Profiles of a Self-Focused Optical Beam in a Plasma*

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Self-focusing of an intense optical beam in a plasma is studied including both the relativistic electron mass effect and the ponderomotive potential effect due to the electromagnetic wave. An exact steady asymptotic solution of beam propagation in a localized solitary wave form is obtained in slab geometry. In the nonrelativistic limit, keeping only the relativistic mass effects, our solution reduces to the solution obtained by Schmidt and Horton.[1] Solutions of oscillatory nature are also presented. Finally, the asymptotic nature of the solitary wave is tested using a recently developed numerical particle simulation code.[2]

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STUDY OF THE MAGNETIC FLUCTUATIONS IN RESISTIVE PRESSURE-GRADIENT-DRIVEN TURBULENCE*

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As a likely cause of fluctuations and anomalous transport in toroidally confined high-β plasmas, the resistive pressure-gradient-driven turbulence has been studied extensively by various authors. Recently, a detailed nonlinear theory of resistive pressure-gradient-driven turbulence was developed in Ref. 1, using simple model which involves only pressure and electrostatic potential fluctuations. Analytic predictions were made for the fluctuation levels and resultant particle diffusivity, and these predictions agreed well with the result of numerical calculations. For the further characterization of the steady state turbulence,[2] the fluctuation spectrum is calculated and shows the spatial structure of the saturated turbulence. This study also reveals the more detailed scale-dependent characteristics of three-dimensional nature of resistive fluid turbulence.

However, understanding of the thermal transport induced by the resistive pressure-gradient-driven turbulence requires information on the associated magnetic fluctuations. The analytic theory of induced thermal diffusivity[3] is derived by using the linearized Ohm's law to calculate the magnetic fluctuations from the calculated electrostatic potential fluctuation. In this paper, we present the results of numerical calculations which include β-scaling of saturated magnetic fluctuation level and wavenumber spectrum.

In going beyond the simple model and the first step toward the implementation of self-consistent model for magnetic turbulence, the evolution of density and electron temperature is followed separately. The results of thermal transport due to parallel electron thermal conduction and magnetic flutter in the fluid regime will be presented.

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ELECTRON TRANSPORT WITH STEEP TEMPERATURE PROFILES AND ATOMIC PHYSICS EFFECTS

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Electron heat transfer is considered along the magnetic field lines in plasmas with strong temperature gradients, when atomic processes may be important. The electron dynamics is modelled with a three dimensional (1-D in space and 2-D in velocity) Boltzmann simulation code which accounts for Coulomb electron collisions with ions and other electrons, as well as for inelastic collisions associated with selected atomic processes. Coulomb collisions are modelled in the familiar Fokker-Planck approximation. The effects of atomic processes on the electron distribution function f and on the distribution of ionisation stages n_q are accounted for by simultaneously solving a set of non linear equations in these variables. The atomic processes retained in the model include collisional ionisation and excitation, and radiative and dielectronic recombination. Simulation results are presented for parameters that are relevant to tokamak scrapeoff and divertor plasmas. The heat flux computed in these simulations is compared with predictions obtained from the usual heuristic flux limited model, and with those of the non local heat transport model proposed by Luciani, et al.[1].

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"Effects of Temporal and Spatial Bandwidth of a Pump Wave on Parametric Instabilities."

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The proposed use of intense sources of wave energy such as a free-electron laser to heat tokamak plasmas has stimulated interest in parametric instabilities that may absorb or reflect the incident pump wave.[1] Using both direct numerical integration of mode coupling equations and analytic solution of equations for ensemble averaged intensities, we have found the effect on the instability growth rate and threshold of both temporal and spatial bandwidth. By spatial bandwidth, we mean a spread in wavenumber of the pump wave. Results in both homogeneous and inhomogeneous plasmas and in one and two dimensions will be presented.

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BALLOONING MODES IN A ROTATING PLASMA*

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Ballooning modes are shown to exist in a non-rigidly rotating plasma, despite earlier expectations to the contrary [1] which were based on the standard ballooning analysis. Using understanding based on wave propgation and geometrical optics we show that such modes can be captured by a WKB representation with an eikonal [2] $\exp\{in[\zeta - q(\psi)\theta - \Omega(\psi)t]\}$, where n is the large toroidal mode number and $\Omega(\psi)$ is the toroidal rotation frequency.

The ballooning mode equation depends <u>explicitly</u> on time. We show that this may give rise to parametric instabilities, as in the Mathieu equation, for large time $t >> |\nabla q|/|\nabla\Omega|$. For shorter time, which includes the typical ballooning growth time, an asymptotic analysis yields an energy principle-like stability criterion. We find that having $\Omega(\psi)$ increase sufficiently rapidly towards the outer surfaces may completely stabilize the ballooning modes on this time scale. Thus it is conceivable that sheared rotation may be used as a transient phase in increasing the plasma pressure to the second stability regime.

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NONLINEAR GYROKINETIC MOMENT EQUATIONS FOR TOKAMAK PLASMAS *

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Nonlinear equations suitable for the study of finite-β nonlinear (ballooning-like) tokamak physics are presented. These equations were derived from the nonlinear gyrokinetic Maxwell-Vlasov system of equations previously obtained through the use of the Action-variational Lie perturbation method of Cary and Littlejohn [1]. Fully electromagnetic effects ($\delta\phi, \delta A_{\|}$, and $\delta \mathbf{A}_{\perp}$) are retained as well as toroidal (magnetic drifts) and finite-Larmor-radius (diamagnetic drifts, and gyrokinetic) effects. These equations will be compared with the moment equations obtained from the nonlinear gyrokinetic equation of Frieman and Chen [2]. In addition, comparison with the equations of Hasegawa and Wakatani [3], and Hazeltine et al. [4] will be made. Finally, a discussion on the potential use of our equations for the quasilinear and nonlinear analysis of ballooning modes in tokamak plasmas will be included.

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Convergence of a Numerical Approximation to the One-Dimensional Vlasov-Poisson System

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A numerical procedure for approximating solutions to the one-dimensional Vlasov-Poisson system of plasma physics is developed and convergence of the approximation to the exact solution is proved. The equations under consideration are

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} + E(x,t)\,\frac{\partial f}{\partial v} = 0 \qquad \text{(a)}$$

$$f(o) = f_o(x,v) \qquad (1)$$

$$E(x,t) = \int_{-\infty}^{x}\int_{-\infty}^{\infty} (f(\bar{x},v,t) - b(\bar{x},v))\,dv\,d\bar{x} \qquad \text{(b)}$$

We approximate the trajectories of (1,a,b) by a kind of Euler method similar to a particle simulation method. A uniform mesh is placed on phase space which divides the region containing the support of the initial data into small squares with length of side h. An approximate trajectory originates at the center of each square. The interval of time [0,T] is divided into small intervals of length Δt. The approximate trajectories are advanced to time $k\Delta t$ based on the field computed at time $(k-1)\Delta t$. The field at time $k\Delta t$ can then be computed. A proof is given that the approximate trajectories converge to the exact trajectories with a truncation error of $O(h+\Delta t)$. All operations involved in the computation can be carried out on a computer without introducing further truncation error.

Resistive Interchange Modes and Ion Temperature Gradient Modes in Heliotron/Torsatron*

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FLR-MHD model[1] to investigate both g modes and η_i modes is derived for heliotron/torsatron configurations by using the stellarator expansion and the averaging over the toroidal direction. Local dispersion analyses show that two unstable branches exist and they correspond to electromagnetic interchange modes and η_i modes, respectively, in the limit of zero resistivity. As for η_i modes, there are two types of η_i modes, 'slab' η_i mode and 'toroidal' η_i mode even in the cylindrical approximation because of existence of average bad curvature in the outer region of the plasma column. The following topics will be discussed in the meeting:
(1) Relations between low-m mode stability and high-m mode stability of ideal interchange modes, and FLR stabilization of ideal interchange mode.
(2) G modes coupled to resistive drift waves and associated anomalous transport given by the renormalized two-point theory.[2] The turbulent diffusivity is enhanced compared with that from the usual g-modes.
(3) Relations between g modes, interchange modes and η_i modes in the cylindrical sheared magnetic field model. For η_i modes Boltzmann relation is assumed for electrons at first, which means $k_\| \neq 0$. While, for the interchange modes, isothermal behaviors are assumed for electrons, which means $k_\| \simeq 0$. In the sheared magnetic field, coupling between g modes and η_i modes is expected.
(4) Fluctuations in the edge region of H-E show broad frequency spectra similar to those in tokamaks.[3] Dependence of the density and potential fluctuations on the plasma parameters are roughly consistent with g modes coupled to resistive drift waves in the low density ECRH experiments.[4] Also H-E experiments show ion thermal conductivity is anomalous, when density profile is flat in the low density ECRH experiment;[5] however, it becomes close to the neoclassical value, when the density profile has more gradient in the NBI experiments. This seems to be consistent with η_i mode driven anomalous ion heat conductivity.

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MOMENTUM TRANSPORT PROCESS IN PLASMA COLLECTIVE MODES*

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A theoretical model is proposed in order to explain the observations concerning the confinement of angular momentum in experiments on magnetically confined plasmas [1] where the rate of momentum transport is found to be larger than predicted by the collisional theory [2]. The considered collective mode is of the so-called electron drift type [3,4] and a resolution of the apparent paradox of having an electron mode responsible for the momentum transfer of the nuclei population is suggested.

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

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THE INTERNATIONAL SHERWOOD THEORY MEETING 1989

Suppression of Wall Field Perturbations in Reversed Field Pinches

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Field errors in Reversed Field Pinches are known to cause a degradation of plasma behaviour and in the last seven years increases in confinement time approaching one order of magnitude have been achieved by systematic reduction of field system errors - winding ripple, plasma centering, gap errors etc.[1] More recently the effect of the radial field perturbations produced by the plasma itself at the vacuum vessel wall has been discussed [2,3,4]. While the exact mechanism is still under contention, all explanations agree that lowering the radial field perturbations b_n at the wall improves plasma performance. As a result a modification to the HBTX RFP ($R/a = 80/26$ cm) at Culham is being designed which incorporates a smooth walled vacuum vessel made of thin graphite (3 mm) backed by a close fitting shell of moderately long time constant (2 mm of copper separated 2 mm from the graphite: vacuum vertical field time constant 20 msec). This poster presents calculations of the suppression of fluctuating magnetic field perturbations at the plasma surface by close fitting layers of conducting material of different conductivities. The results are expressed in terms of the value of $b_n/b_{\parallel}$, the ratio of the amplitude of the radial field at the plasma surface to the tangential field applied by the plasma, usually known from measurements, as a function of frequency and wave number. For example, in certain parameter regions, the normalised radial field is proportional to the distance of the (poorly conducting) vacuum vessel from the (highly conducting) shell. This distance is reduced from 30 mm in previous assemblies of HBTX to 6 mm with the smooth wall outlined above.

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Effect of Density and Temperature Gradients and Shear on the Dipole Vortex Solution of Drift Wave Plasma*

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The generalized equation for a quasi-two-dimensional electrostatic drift wave, which includes the density and temperature gradients of the plasma, is studied theoretically and numerically. The well-known Petviashvili equation for drift solitons is revised to take into account the plasma nonuniformity. Studies of the revised equation show that the dipole vortex solutions of the Hasegawa-Mima equation split up into long-lived monopole vortices (cyclones and anticyclones) due to the presence of a small temperature gradient alone, or a small density gradient alone.

The effect of magnetic shear on the monopole drift wave vortex is also studied analytically and numerically. The results show that even small shear can cause non-perturbative changes of the solitary wave, which result in radiation. This non-perturbative effect can be interpreted to be due to the sensitivity of a homoclinic orbit in Hamiltonian theory. A homoclinic orbit represents a monopole vortex at zero shear, which in turn can be viewed as a point spectrum of a nonlinear eigenvalue problem. The point spectrum for a one-valued amplitude of the monopole vortex at zero shear with a single separatrix homoclinic orbit, is found to change into a continuous spectrum of nonlinear eigenvalue solutions with radiative tails that couple to exterior ion acoustic waves. The eigenvalues that correspond to the critical amplitude for the existence of the monopoles, are numerically and analytically found and interpreted.

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A Self-Consistent Theory of Radial Transport of Parallel Current by Microturbulence

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The radial transport of parallel current by microturbulence is a potentially important agent for relaxation in reversed field pinch plasmas. In particular, significant transport of current is possible if electric and magnetic fluctuations scatter current-carrying electrons over the radial extent of the plasma in one mean-free time. Such a process has been proposed as the mechanism for relaxation and reversal maintenance in low collisionality RFP plasmas[1,2]. In the aforementioned work, radial transport of current carrying electrons was tied to streaming along static, stochastic magnetic fields.

In this work, we consider the radial transport of parallel current due to collisionless microturbulence. *The effects of temperature anisotropy and of a radial temperature gradient are included in a self-consistent theory.* We show that self-consistency constraints which arise from consideration of electron mode coupling inhibit current transport due to magnetic fluctuations, even in the presence of temperature gradients, etc.[3,4]. Thus, electrostatic fluctuations which couple to ions regulate relaxation. We further show that the radial flux of parallel current is dirven by off-diagonal terms and is, in general, insufficient to account for the RFP 'dynamo'. Finally, the status of the 'kinetic dynamo' and the results of recent related experiments are discussed in the context of the developments discussed here.

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STABILITY OF SEMICOLLISIONAL MODES IN DIVERTOR TOKAMAKS

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An improved confinement regime, known as H-mode has been observed since 1982 in several auxiliary-heated Tokamaks. Common features of these experiments seem to be, among the others, the presence of a magnetic separatrix quite close to the plasma boundary, the existence of a threshold in the edge electron temperature for the achievement of the H-mode, and the observation of electron density and temperature profiles rather flat over the whole radius with marked pedestals at the edge.

In the past few years, microinstability based models of anomalous transport have been proposed by several authors in order to correlate the experimental trends in tokamak transport with small scale turbulence. Regarding usual ohmic or auxiliary-heated L-mode discharges, it has been shown that these models may account for the confinement properties in the region between the q=1 and q=2 surfaces, the so called good confinement region; different physical mechanisms must be instead invoked to model transport in the region beyond the q=2 surface, where the low values of edge temperature depress the microinstability based diffusivities. Concerning H-mode discharge, the density and temperature profile features indicate that the role of good confinement region is possibly played by the region beyond the q=2 surface. Therefore, in order to understand the global confinement properties of the discharge, it is necessary to investigate the mechanisms which can determine the transport in the new confinement region. Due to the high edge temperature values, the role of microinstabilities in contributing to the anomalous transport coefficients may be important, in principle, differently from the ohmic and L-mode cases. Moreover microinstabilities may still be relevant in determining transport in the internal region where the reduced gradients may be consistent with the locally improved confinement.

The aim of this paper is to examine if the stability of toroidal semicollisional modes, belonging to the electrostatic drift branch, destabilized by ion temperature gradients and trapped electron dynamics, may be affected by the presence of a magnetic separatrix.

It is shown that, in the limit of flat density profile, the separatrix makes the η_i threshold to increase, consistently with the improved confinement observed in the flat density region of the H-mode discharges. In the steep density gradient limit, unfavourable stability properties of the equilibria with the x-point outside the torus are evidenced, which could be correlated with the difficulty encountered in obtaining the H-mode in such configurations.

Finally, the stabilizing effect of the separatrix on the trapped electron modes is demonstrated, which could further support the interpretation of the reduced transport in H-mode discharge in terms of microinstability based models.

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Ballooning Stability Optimization of Helias Equilibria

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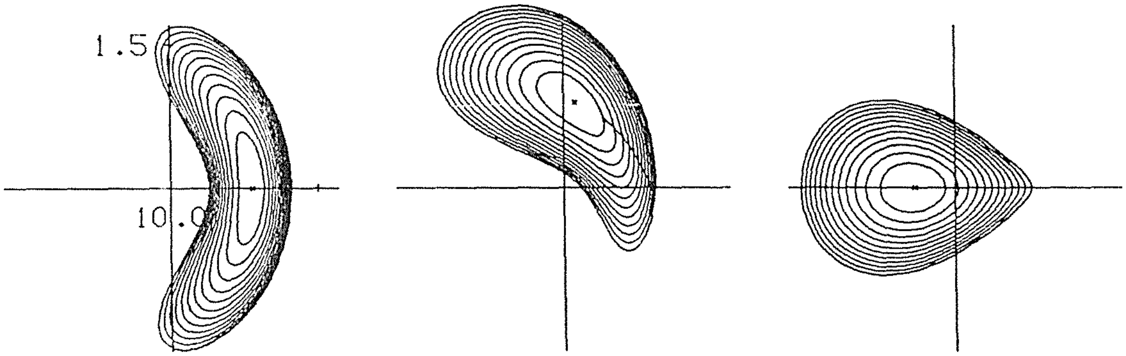
As an extension of previous ballooning mode calculations [1] small-shear equilibria have now been evaluated with respect to their localized ballooning mode stability over the entire plasma cross-section with the following procedure. Typical values of the rotational transform in Helias equilibria with 5 periods and aspect ratio 10 envisaged for W VII-X are $0.8 \lesssim \iota \lesssim 1.2$. The value of ι of a given equilibrium is shifted to the nearest rational value reasonably resolvable and incommensurable with the number of periods, e.g. $\iota = \frac{7}{8}$, by computing a neighbouring equilibrium with a small longitudinal current which does not significantly change the ballooning stability properties but allows a mode to be shifted through the plasma, a procedure which may also correspond to an actual experimental situation. Thus, a pressure profile optimization can be done and equlibria be obtained which are ballooning-stable across the cross-section. A direct incorporation of the ballooning mode stability analysis into a configuration optimization procedure appears to be too time-consuming at present. Instead, analysis of the typical ballooning mode behaviour found in Helias equilibria suggests that a measure of the driving term of the ballooning instability be used at the point of most unfavourable curvature. Preliminary results indicate that equilibria which are stable against resistive interchanges and ballooning modes at $\langle\beta\rangle \approx 0.05$ can indeed be obtained. Flux surface cross-sections of an example are shown in the figure.



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PARAMETRIC TURBULENCE EFFECT ON LH HEATING AND CURRENT DRIVE

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The acceleration of electrons and ions under the effect of the parametrically excited plasma turbulence is studied. The influence of LH collapse is discussed. It is shown that the parametric turbulence sharply increases the current drive efficiency. The explanation of the current drive density limit is presented.

Sherwood Theory Meeting
April 3,5, San Antonio, Texas

PARTICLE CONFINEMENT IN REALISTIC 3D ROTAMAK EQUILIBRIA

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Abstract

Steady-state toroidal current I_θ (with associated poloidal field $\bar{B}$ and flux surface Ψ) is required to confine the plasma in a steady-state toroidal magnetic fusion reactor. The rotamak[1-2], an unorthodox toroidal plasma confinement device employs a magnetic field b_ω rotating at a low frequency f to give a net toroidal drift velocity u_θ to electrons (but not ions) and so produce the required I_θ.

We show for electrons that (i) the rotating field causes a rotating tilt $\sim b_\omega/\alpha\bar{B}$ of the effective flux surfaces, where α is the ellipticity of the separatrix (small α corresponds to prolate, i.e. long in the z direction), (ii) electrons are imperfectly confined to these tilted flux surfaces, and in addition, (iii) the electrons are confined within a three-dimensional potential well of magnitude $\approx ef\Psi(r,z)$, which has essentially the shape of an *untilted* flux surface. Thus, electrons rattle around in the potential well, shifting from one tilted flux surface to another until their orbit has filled up the entire volume of the potential well. For ions: (i) Providing that the ion velocity is sufficiently slow compared to the rotation of the tilted flux surface, the ions see only the average of the tilted flux surface, which is just the original untilted flux surface and so are confined in the usual way, and (ii) the potential well reverses sign and so becomes a potential hill. Hence, ions are confined by momentum conservation, not energy conservation, whereas the opposite is true for electrons. Geometrically, the electron and ion confinements differ substantially: the electrons are confined to a volume (the potential well volume), whereas ions are confined to a surface (the flux surface).

We postulate that the helical Rhythmac[12] configuration probably also has a related, but helical-like tilt; however, due to the Rhythmac's helical symmetry, it is likely that electrons will be confined in stellarator-like fashion to rotating helical flux *surfaces*, and unlike the rotamak will not rattle around in a *volume*.

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Theoretical Studies of Profile Control Using Lower Hybrid Current Drive and Electron Cyclotron Resonance Heating*

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Suppression of sawteeth and access to a high beta ("second stability")[1] operating regime may be vital in order to operate a tokamak as a fusion reactor. Sawtooth stabilization would improve central plasma confinement and access to second stability would improve the parameter space accessible to D-T fusion reactors, reduce requirements on driven current in a reactor (due to increased bootstrap current), and permit the use of tokamaks for advanced fuel reactors. Suppression of sawteeth by electron cyclotron resonance heating (ECRH) near the $q = 1$ surface has been demonstrated in numerous experiments (for example DIII-D and T-10). Also, it has been shown[2] theoretically that a sequence of MHD equilibria exist which allow a stable path to a high beta operating regime in shaped plasmas with $q(0) \gtrsim 2$ and $q(a) \simeq 7$. Current profiles with $q(r) \gtrsim 2$ everywhere in the plasma can be achieved via off-axis RF current generation.

In order to study current profile control using lower hybrid current drive a simulation model[3] has been modified for noncircular equilibria and combined with an MHD equilibrium solver.[4] New equilibria are calculated in the presence of the RF current drive so that the final tokamak equilibrium and the RF current generation are self-consistent. It is shown that for a configuration with $R_o/a = 3$, $q(a) \simeq 7$, $B_\phi = 1T$, elongation $\kappa = 1.4$, $T_e(0) = T_i(0) = (1.5 - 2.0)$ keV, and $n_e(0) = 3 \times 10^{19} m^{-3}$, it is possible to raise q(0) from 1.0 to $q(0) \gtrsim 2$ by generating RF current on the order of $I_{RF}/I_p \gtrsim 0.6$, with $I_p = 150$ kA and $P_{LH} = (0.3 - 0.4)$MW. Lower hybrid current profile control in an ITER configuration has also been studied.

Finally, a ray tracing and absorption package[5] has been used to study ECRH in the Compact Ignition Tokamak (CIT). Central absorption has been found in the range $B_\phi = (7.5 - 10)$T at $n_e(0) = (2 - 8) \times 10^{20} m^{-3}$ and $T_e(0) = (5 - 20)$ keV, using $f_o = 280$ GHz. It has been found that the power deposition profile can be controlled by changing the incident wave propagation angle, with launch angle $\gtrsim 30^o$ normal to $\mathbf{B_o}$. It therefore appears possible to do localized ECR heating near the $q = 1$ surface even in the core of a burning plasma $[n_e(0) \gtrsim 8 \times 10^{20} m^{-3}$ and $T_e(0) \simeq 20$ keV].

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One and Two Dimensional Modelling of the RFP Dynamo Effect*

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Fast running codes for modelling the RFP are needed for guidance in the design and operation of the equilibrium feedback control of ZTH, the next generation Los Alamos reversed-field pinch (RFP). An interesting and prominent feature of the RFP is the toroidal flux generating dynamo effect which, although complicating the determination of appropriate transport coefficients, experimentally sustains the reversed field configuration against resistive diffusion.[1] Such sustainment has been demonstrated with 3-D MHD calculations in the past.[2,3,4] Our aim is to explore means for incorporating the essential dynamo features into practical one and two dimensional calculations representing mean-field RFP configurations. In this paper we focus on the properties of a diffusive form[5,6,7] of a hyper-resistivity correction term to Ohms Law which, when incorporated into an axisymmetric toroidal resistive MHD code, allows RFP formation and sustainment.[8] For this model which only includes a dynamo electric field $\mathbf{E}_D$ parallel to $\mathbf{B}$ (i.e. an α effect $\mathbf{E}_D = \alpha\mathbf{B}$) the mean-field steady-state uniform loop voltage is given by the mean-field value of $2\pi R\eta_{\perp}J_{\phi}$ evaluated at any major radial coordinate R on the reversal surface of the toroidal mean-field. In the absence of appropriate 1-D and 2-D transport coefficients for a driven relaxing RFP, we utilize temperature and density profile modelling consistent with observed values of experimentally measured parameters. We report the results of a parameter study of the loop voltage,both during startup and steady-state using the time-dependent 2-D MHD code together with 1-D and 2-D steady-state calculations. Comparisons between these modelling results and existing Los Alamos RFP data will be shown. We discuss the possible need of an improved hyper-resistivity term as more detailed RFP plasma temperature and density, as well as internal magnetic field measurements become available.

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SHERWOOD THEORY MEETING 1989

Guiding Center Drift in a Rotating Tokamak Plasma*

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A variational principle for guiding center motion has been derived by Littlejohn[1] in the drift ordering in which all flows are assumed to be less than the thermal speed. The resulting drift equations conserve phase volume but do not allow for large flows. MHD ordering is appropriate when large electric fields may produce flows on the order of the thermal speed (in the sheath region or during the onset of a disruption). Also, large toroidal flow has been observed in early toroidal pinch experiments[2]. An MHD-ordered Lagrangian derivation of phase-volume conserving drift equations which allow for large flows is presented and specialized to a rotating tokamak plasma. The associated Hamiltonian is written in tokamak coordinates. This work may have application in the study of orbits near the sheath region for alpha particle wall bombardment.

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THREE-DIMENSIONAL FLUID COMPUTER CALCULATIONS OF ION TEMPERATURE GRADIENT DRIVEN INSTABILITIES*

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Three-dimensional fluid computer calculations of ion temperature gradient-driven instabilities or η_i modes have been performed in cylindrical geometry. To do so, ion temperature and ion parallel evolution equations have been imported into the initial value code KITI.[1] The new code KITI can be run in the finite beta mode as well as in the electrostatic limit. We have tailored the q, ion temperature and density profiles, so as to approximate a sheared slab, i.e., L_S/L_n is approximately constant over the whole minor radius.

Linear stability calculations indicate that a large amount of dissipation is required to stabilize high-m modes with large radial wave numbers for values of η_i ranging from 1 to 10 and L_s/L_n from 10 to 100, the less so as η_i gets closer to its (fluid) threshold value of 2/3 and as L_s/L_n decreases.

To obtain a scan of parameter space, multi-mode single helicity calculations with background ion temperature gradient relaxation have been carried out with two different types of profiles. Type I is where the density profile is fixed and the temperature profile steepens as η_i increases and type II is where the temperature profile is fixed and the density profile flattens as η_i increases. Saturation occurs by preferential modification of the equilibrium temperature gradient. Fluctuations have the following features at saturation: ion temperature fluctuations exhibit a weak $\eta_i^{1/2}$ scaling and a linear increase with L_s/L_n, the density fluctuations (on the order of the potential fluctuations) are down by a factor of order η_i from the ion temperature fluctuations. Type II profiles exhibit a lower level of fluctuations since the pressure drive decreases as η_i increases. Also, there is a definite tendency for the modes to broaden in radius as saturation is achieved.

Results from multiple helicity, nonlinear calculations with equilibrium profiles maintained will also be reported.

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TOROIDAL EQUILIBRIUM OF PLASMA-BEAM SYSTEMS

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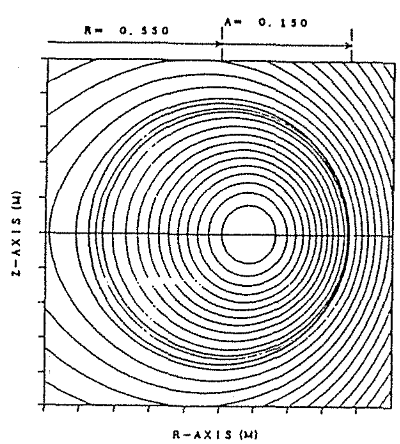
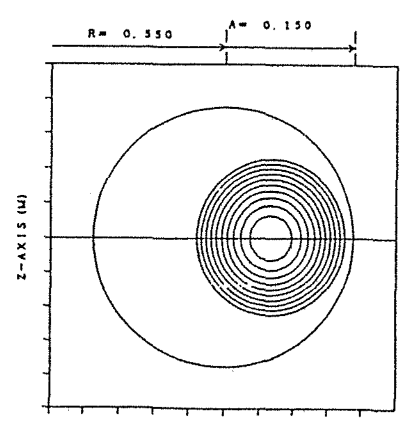
Toroidal equilibrium model of plasma-beam system has been formulated and numerically analyzed. The model can be applyed to various type of plasma-beam equilibria such as beam-core plasma confinement configurations, tokamaks with strong runaway electrons and/or with intense ion beam injection. The model equations are coupled nonlinear elliptic partial differential equations; One is a Grad-Shafranov type of plasma equilibrium equation with additional beam current terms, which governs the flux function ψ, and the other is a beam equilibrium equation which governs the beam-velocity stream function ϕ. The incompressible three dimensional plasma-beam equilibrium equations are (2+3)-hyperbolic and 4-elliptic partial differential equations. The two of the characteristic curves are degenerated to the direction of magnetic fields, and the rest four are degenerated to the direction of the beam velocity, which corresponds to the Hamilton-Jacobi characteristics of the collisionless beam dynamics. We need five independent noncharacteristic Cauchy data to determine an equilibrium. In the axisymmetric formulation. we characterize an equilibrium with specifying distributions of plasma pressure $p(\psi)$, poloidal plasma current $I(\psi)$, beam density $n(\phi)$, beam angular momentum $A(\phi)$, and the beam Hamiltonian $h(\phi)$. Figures show an example of numerically calculated plasma-beam equilibrium with plasma current = 90 kA, beam current = 10 kA, external toroidal field (center) = 2 T. Figure (a) plots the contours of the flux function ψ on a poloidal cut plane of the torus. The major and minor radii of the limiter are .55 m and .15 m, respectively. The free boundary of the plasma is shown by the bold face curve. Relativistic electron beam orbits are shown in Fig.(b). The beam particle energy is 5.1 MeV.



(a)



(b)

QUIVER KINETICS*

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Abstract

The near fields in the edge plasma of a radio frequency heated tokamak can cause one or more charged species to oscillate in the applied field with a quiver (or jitter) speed comparable to its thermal speed. By retaining the quiver motion as well as the gyromotion a reduced kinetic or quiver kinetic equation is derived. Because of the fast time and gyrophase averages only the evolution of the slow time and gyrophase independent portion of the distribution function is determined. The quiver kinetic approach is nonlinear but does not employ a resonant quasilinear operator since nonresonant, wave particle interactions dominate in an edge plasma subject to intense rf fields. The ordering adopted permits the species quiver speed u_j in the intense rf fields to be on the order of the species thermal speed v_j and the wave frequency ω to be on the order of the cyclotron frequency Ω_j. As a result of the $u_j \sim v_j$ ordering neoclassical effects are negligible as long as $1 \tilde{>} (u_j/v_j)^2 \gg \rho_j/\ell$, where $\rho_j = v_j/\Omega_j$ is the species gyroradius and ℓ the scale length. The quiver kinetic equation is developed for arbitrary geometries and so can be used to investigate non-axisymmetric effects in a tokamak edge plasma in the absence of cyclotron and Landau resonances.

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NUMERICAL SIMULATIONS OF SAWTEETH IN TOKAMAKS

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Abstract: Numerical simulations of sawteeth in tokamaks have been carried out using reduced magnetohydrodynamics and a simple transport model. The electron temperature is evolved self-consistently including ohmic heating and a highly anisotropic thermal conductivity. The simulations reproduce experimental results for sawtooth period and collapse time from ohmic discharges with Lundquist numbers S up to 10^7.

The sawtoothing is found sensitive to the values of the transport coefficients. In particular, the perpendicular viscosity ν must be comparable to, or larger than, the perpendicular heat conductivity $\chi_\perp$ for distinct relaxation oscillations to occur. To study the scaling with S , ν and $\chi_\perp$ have been scaled as 1/S, and S has been varied. Modifications of the equilibrium, caused by the sawteeth, play an important role for the scaling of collapse time and period with the Lundquist number. The self-consistently computed q-profiles are very flat in a central region where $q \approx 1$. Outside the low-shear region, the shear rises sharply. This q-profile allows a resistive mode to be turned on quickly with a high growth-rate. The deviation of the central q from unity over the sawtooth cycle decreases for increasing S, and the collapse time shows a weaker dependence than the expected $S^{1/2}$ scaling.

SHERWOOD THEORY MEETING 1989

Modification of $m = 1$ Kink Mode Theory Due to Arbitrary Larmor Radius and Hot Electrons*

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Several investigators have reported the modification of $m = 1$ kink mode theory in the presence of hot ions. It was shown that the hot ion precessional branch and the ion ω_i^* mode are related to each other and the two modes merge for the appropriate set of parameters. It was further shown that hot trapped ions can enhance stability if their pressure gradient decreases radially inside the $q = 1$ surface. We also note that the fluid treatment for the ω_i^* branch can fail because the boundary layer of the eigenmode becomes comparable to the ion Larmor radius. We present two new results: 1) the effect of hot electrons is assessed and it is shown that the precessional mode and ω_i^* mode are now separate, 2) enhanced stability from hot electrons is attained only if their pressure gradient increases at the $q = 1$ surface, a situation that is possible to achieve experimentally (the hot electron pressure gradient then decreases outside the $q = 1$ surface). A kinetic model was developed to take into account the effects of arbitrary ion Larmor radius, and an analytic solution has been obtained. The kinetic effects are found to be more destabilizing than the predictions of the fluid theory.

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SHERWOOD THEORY MEETING 1989

Saturation of a Single Mode in High Energy Particle Driven Systems*

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In ignition systems Alfvén wave instability can arise from the free energy of the alpha particle density gradient. Characteristically the excited modes, such as the Toroidal Alfvén Gap Mode, is in a discrete quantized state, and the instability source is perturbative (like the classic bump-on-tail instability). With this motivation, a formalism has been developed to calculate the saturation of a single mode driven by a high energy particle source. The formalism is first developed for the bump-on-tail instability, where particles are injected at high energy, slow down and pitch angle scatter, and interact with a single mode (particle annihilation is also included in order to have $\partial f/\partial v > 0$, where f is the distribution function and v the speed). This paradigm problem is then extended to the electrostatic drift wave problem in a sheared magnetic field and the Alfvén wave alpha particle problem in the limit $\omega \ll \omega^*$ (ω^* is the drift wave frequency of hot particles). The physical effects of these problems can be described with a formalism similar to the bump-on-tail problem. Several generic results have been found 1) when the bounce frequency first exceeds the rate in which trapped particles are lost, the linear growth rate is enhanced; 2) when diffusive effects are negligible in the drift wave and Alfvén wave problems, trapped particles are locked into resonance and cross the magnetic field as they slow down; 3) in the relevant physical situation, trapped particles are lost by pitch angle scattering, and saturation is determined by the condition $\omega_b^3 \gtrsim \nu_d \omega^2 P_L/P_d$, with ω_b the trapped particle frequency. For the Alfvén wave problem $\omega_b^2 \simeq m^2 V_A^3 q \delta B / L_s r_0^2 \omega_c B$ with m the poloidal mode number, V_A the Alfvén speed, δB the perturbed magnetic field, L_s the shear length, r_0 the minor radius location of the mode, ν_d is the pitch angle diffusion coefficient and q the safety factor at r_0, ω the mode frequency, P_L the linear rate alpha particle pumps energy into the wave, and P_d the rate in which energy is extracted from the wave by dissipation with the background plasma (for linear instability $P_L/P_d > 1$).

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SHERWOOD THEORY MEETING 1989

δF Algorithm for the Integration of the Electrostatic Gyrokinetic Equation*

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We discuss a numerical algorithm for integrating the electrostatic gyrokinetic equations which calculates the field at the next time step by first solving implicitly the linearized eigenmode equations and then increments the particles using the calculated fields. The particle distribution function F is separated into two parts: $F = \delta F + F_0$, where $\delta F \ll F_0$, and F_0 is a prescribed distribution function (for example, the equilibrium distribution function). The algorithm focuses on "time-stepping" δF, a procedure developed by M. Kotschenreuther to reduce noise levels. This algorithm has been tested in a code which time-steps δF on a grid in phase-space. It is stable independent of $k_{\|}v_{\|}\Delta t$. The results for the linear growth of η_i-modes in a sheared-slab are in agreement with the linear theory. The progress in the nonlinear aspects of this calculation will be discussed.

1. Institute for Fusion Studies Report No. 360, "Particle Simulation With Greatly Reduced Noise," M. Kotschenreuther.

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

Non-Thermal Modification of the Current Profile in a Tokamak by Electron Cyclotron Heating.

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The interaction of the tokamak DC electric field with a group of energetic electrons may result in the enhancement of the ohmic current. Here we study the case of the superthermal tail created during the Electron Cyclotron heating and its effect on the current profile. We study the modification of the conductivity as a function of the wave-packet parameters (frequency , parallel refractive index and power) as well as a function of the wave-packet trajectory . The efficiency of the process is obtained in two steps: first, solving the relevant adjoint problem for the incremental conductivity as a function of the energetic electrons momentum and then, finding the maximum of the RF power deposition in momentum space as a function of the wave-packet parameters. The theory is applied to study the sawtooth stabilization for typical experimental conditions : we show by means of a Fokker-Plank code that when the EC resonance layer is near the q=1 surface the increased conductivity may result in a local flattening of the q profile, a result that is independent of the shape of the temperature profile. A flattened q profile can give rise to improved stability, and may explain the lengthening of sawtooth periods observed in many ECRH tokamak experiments. The characteristics of the electron distribution function during ECRH are discussed and it is shown that a hot trapped population is generated near the resonance layer.

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STABILITY OF MAGNETIC VORTICES*

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A method of analysis, previously used to study the propagation of waves along the axis of quantum vortices in super-fluid helium[1], is applied to study the stability of vortices in a magnetized plasma. By restricting the analysis to long wave length disturbance it is possible to obtain explicit stability criterion, and where applicable growth rates, for monopolar, dipolar and linear strings of magnetized vortices.

A non-linear theory is developed to illustrate the initial formation of strings of vortices.

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ABSTRACT

Fast Ion Thermalization in a Hot Deuterium Plasma

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Fusion products[1] are tracked by Monte Carlo simulation[2,3] to thermalization in a fully ionized plasma. Ion recoils from scattering is also treated. Ranges and times to thermalization at a variety of plasma temperatures will be presented.

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EDGE ELECTRIC FIELD EFFECTS ON ORBITS IN TOKAMAKS AND STELLARATORS*

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Radial electric fields in both tokamaks[1] and stellarators[2] can pass through zero as a function of radius near the plasma edge–at least under some circumstances. In addition, it has been suggested that the L and H modes are correlated with the electric field.[3] Since particles that lie on orbits that pass beyond the "last relevant flux surface" can be promptly lost,[1,3] it is important to understand how the orbit topology changes with changes in the electric field.

Here we examine the effect of electric field on orbits near the "last relevant flux surface" for both tokamaks and stellarators. The effect of a zero crossing of the electric field is contrasted with cases in which the electric field is more nearly constant. Particular attention is given to delineating the regions of velocity space that have crescent or banana shaped orbits. The role of near cancellation of poloidal motion induced by rotational transform with $E \times B$ drift is discussed, and simple analytic expressions are given. Estimates of the prompt particle losses for the different electric fields are given.

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TRANSPORT BARRIER IN SIMULATIONS OF η_i TURBULENCE*

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The η_i mode is a negative compressibility instability driven by an ion temperature gradient. The density gradient is stabilizing and in a collisionless plasma produces a threshold $\eta_i = d\ell n(T_i)/d\ell n(n) \stackrel{\sim}{>} 2$ which must be exceeded for instability. We examine the role of the density profile in controlling energy confinement in a 2-D heated plasma slab. A set of nonlinear fluid equations describing the long wavelength η_i mode are integrated in time. The 3-D equations are reduced to 2-D by assuming $\partial/\partial z = \alpha\partial/\partial y$ with α a constant. Dissipation at short wavelengths is modeled by diffusive damping. In simulations with broad density profiles the ion temperature rises until the transport caused by the η_i mode turbulence balances the heat input. For weak heating the temperature profile is close to marginal so that $\eta_i \approx 2$ and $T_i(x) \sim n^2(x)$. A sequence of simulations are completed for successively narrower density profiles. Profiles narrower than a critical value exhibit an abrupt transition to a much higher peak ion temperature and the profile is no longer given by $T_i \sim n^2$. For H mode density profiles the global transport is greatly diminished by the existence of a transport barrier in the region of large density gradient near the plasma periphery.

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STREAMERS DRIVEN BY THE ION TEMPERATURE GRADIENT INSTABILITY*

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The η_i mode is an instability driven by negative compressibility in the presence of an ion temperature gradient. In this paper, we study the nonlinear evolution of the η_i mode. We use fluid equations valid for long wavelengths ($k_\perp \rho_i \ll 1$). Dissipation at short wavelengths is modelled by diffusive damping. Our study centers on a 2-D heated slab model, both with and without shear, in which the density profile is held fixed. For zero shear, the resulting instability evolves to a quasi-one-dimensional state containing elongated "streamers" whose radial extent is of order the density gradient scale length. This is consistent with $k_\perp \rho_i \ll 1$ and allows for thermal transport comparable to the Bohm rate. For these streamers, the nonlinearity due to advection by the parallel velocity can become comparable in importance to that due the $\vec{E} \times \vec{B}$ advection. We have made a detailed analytical and numerical study of the saturation of the η_i mode by this parallel nonlinearity. For moderate but nonzero shear, the elongation of these structures can still be large compared with ρ_i, in which case our equations remain valid. We will present a study of the effects of shear on the streamers in the 2-D heated slab model.

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COMPUTATION OF MAGNETIC COORDINATES AND ACTION-ANGLE VARIABLES*

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Algorithms in use for the calculation of magnetic coordinates in three dimensions[1,2] reconstruct the coordinates from information obtained by following magnetic field lines. These algorithms are inefficient near low order rational surfaces, where the field line must be followed over a great distance to adequately sample the corresponding flux surface. Iterative methods of sampling the flux surface naturally suggest themselves. Such methods have been extensively developed in the context of the calculation of action-angle variables for atomic and molecular systems[3,4] and also for application to high energy particle accelerators.[5] (Magnetic coordinates correspond to action-angle variables for the Hamiltonian flow defined by the magnetic field lines.) Iterative methods do not see the same degradation in efficiency near rational surfaces. Iterative methods, however, display numerical instabilities, in contrast to the field line following methods, which are robust. We have developed a new code which uses information obtained by field line following both in the formulation of an iteration procedure and to provide initial conditions for the iteration. This appears to combine the best features of both methods.

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Local Kinetic Stability Analysis of the Ion Temperature Gradient Mode

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A local dispersion relation is derived for the toroidal ion temperature gradient mode, retaining full drift resonance effects but assuming small ion Larmor radius and fluid-like parallel ion response. The effects of finite ion Larmor radius, sound wave coupling, and impurity ion species are studied. The dispersion relation is analyzed for marginal stability, in the limit of flat density profiles, to obtain the critical ion temperature gradient length. The result of the analysis is that all three of the effects considered have a stabilizing effect, with the Larmor radius and sound wave coupling being the strongest. The combination of these effects lowers the critical value for stability (for flat density profiles) to $L_{T_i}/R \approx 0.2$ ($L_{T_i}^{-1} = |\partial \ell n T_i / \partial r|$), a result previously conjectured in numerical simulations [1]. The relation between present results and anomalous transport in the L and H–modes is also discussed.

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Radiative Collapse of a Bennett-Relaxed Z-Pinch*

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We have been exploring the utility for RFP physics of assuming a relaxed state consisting of ions and electrons, each in a rigidly drifting and rotating isothermal Maxwellian distribution. This speculative approach has the pragmatic feature of possessing phenomenologically useful global parameters such as drift velocity and temperature that vary in accordance with global physical quantities such as energy and entropy. Indeed such a relaxed state can have a reversed toroidal field. In this model, the plasma gains energy from a time-dependent electric field by means of Poynting's vector; the energy exchanged between the electrons and ions through Coulomb collisions is calculated with a Fokker-Planck treatment analogous to that used by Dreicer[1] to calculate runaways.

Before we sink this model's teeth into RFP physics, we are cutting its teeth on the physics of radiative collapse of a Z-pinch. For this physics, the self-consistent relaxed state is that of Bennett.[2] We are initially simplifying the treatment of this problem by assuming that the ions are cold, but in quasineutral equilibrium with the electrons. Three parameters then specify the electrons: the drift velocity, the on-axis number density, and the temperature. In our model, their evolution is governed by the constancy of the electron's line density and the evolution equations for total energy (i.e., thermal, fluid-kinetic, and magnetic) and entropy. Entropy is gained through electron-ion collisions and is lost through bremsstrahlung. One should note that the Bennett profile does not have the flaw of a logarithmically divergent fluid-kinetic energy suffered by the isothermal parabolic number density (constant current density) model.

For a variety of initial conditions and time-independent applied electric fields, initial results indicate that the pinch evolution always culminates in a time-independent (attractor) state whose current is the Pease-Braginskii current[3] and whose final radius is proportional to (line density)$^{3/4}$/(electric field)$^{1/2}$. Before the final state is attained, the pinch may bounce toward and away from a highly collapsed state. Our model calculations allow also a time-dependent electric field or a time-dependent pinch current to be specified. We finally wish to note that for the case of a Bennett pinch, the classical limit of the resistivity is attained when the line density is much greater than $4\pi m_e/e^2\mu_0$; i.e., $3.55 \times 10^{14}\ m^{-1}$.

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Stability of an FEL E-beam in a Corrugated Waveguide *

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To reduce eddy losses in the waveguide region of the FEL wiggler it has been suggested that a corrugated waveguide be employed. Such a configuration is under consideration for CIT. This choice changes boundary conditions at the wall and thereby reduces the tangential magnetic field and thus the surface current. This choice also generates a slow cavity mode which can destabilize modes driven by the electron beam. We study this effect on longitudinal and transverse modes. In the longitudinal mode we find instability provided $d/b >> 1/4\gamma^2$, where d is the depth of the corrugation (typically a 1/4 of the laser wavelength), b is the waveguide radius and γ is the beam energy. The convective growth is

$$\Gamma < \frac{2z}{b}\left(\frac{4I}{17,000\text{amps}}\frac{1}{\gamma^3}\right)^{1/4} \approx 5$$

We will also describe results for the transverse mode.

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TRANSPORT OF CHARGED PARTICLES INTERACTING WITH COHERENT WAVE-FIELDS IN A TOKAMAK PLASMA*

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ABSTRACT

Using a test particle model, we investigate the effects of coherent wave-fields on the spatial transport of particles in a tokamak. This is in contrast to usual transport analyses which assume that the fields are of random phase [1,2]. If one assumes that the fields are coherent, then the random phase assumption inherent in the previous analyses is of questionable validity. For example, it has been shown that correlations in two dimensional hamiltonian chaos drive the local diffusion coefficient into oscillations about the random phase value [3,4]; such models have been proposed for studying the velocity space diffusion of tail particles in an RF heated tokamak [5,6]. We extend these studies by coupling the chaos in velocity space to configuration space, thereby obtaining the spatial transport of particles across flux surfaces.

For illustrative purposes the model we consider is that of a periodic interaction of circulating super-thermal electrons with a localized oscillating ($\omega \ll \omega_{ce}$) parallel electric field in a tokamak (relevant to lower-hybrid current drive). A two dimensional area preserving map is developed to describe the parallel dynamics. The radial drift of an electron is studied by integrating the drift equation where the parallel velocity appears as a driving function determined by the dynamical map. The radial diffusion of an electron in the stochastic region of parallel phase space depends sensitively on the localization and coherence of the fields. Furthermore we have found anomalous behavior in the vicinity of primary islands of the parallel map; particles oscillating in these structures are convected radially by the drift motion.

We propose to carry out this type of study for other RF heating and current drive schemes, e.g. ICRH and ECRH.

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Collisional Effects on Low Frequency Turbulent Transport of Flux, Particles, and Energy in a FRC

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A recent stability calculation found three distinct unstable modes in three distinct regions of the Field Reversed Configuration (FRC). Transport estimates for the parameter range of present devices showed good agreement with experiment, giving confinement times scaling roughly as Ba^2/T. The present work extends the calculation of transport produced by these three low frequency modes to a variety of collisional regimes, and obtains both global transport scaling estimates and local transport coefficients as a function of the collision frequency. The result is that low frequency drift wave transport still agrees with most present experimental measurements of particle, flux, and energy loss both in terms of magnitude and scaling, but that the scaling changes to increase the confinement by $\omega_{ci}a_i^2/\nu r_s^2$ for plasmas with very low collisionality, and increases the confinement by $(\omega_{ci}a_i/\nu r_s)^{-1}$ for plasmas with high collisionality. "High" and "Low" will be defined and plots of confinement time vs. ν presented.

Three-Dimensional Flux-Tube Dynamics*

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By means of a 3-d particle code, we study the evolution of magnetic flux tubes, alone and in pairs. The single flux tube is subjected to differentially rotating boundaries. It is found to develop a local kink-like instability which reconnects the magnetic field, redistributing the energy to the particles in the plasma. These observations are consistent with those reported by Zaidman *et al.* (Ap. J., to be published, March 1989) and Otani and Strauss (Ap. J. **325**, 468 (1988)). We also study the coalescence of two parallel flux tubes. The tubes pinch together, non-uniformly in z, finally combining to produce a turbulent increase in plasma energy. We give results of 2-d simulations for comparison, as well as details of the three-dimensional simulations.

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Effects of Temperature Anisotropy, Rotation and Collisions on η_i Mode in the Columbia Linear Machine*

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The ion temperature gradient driven η_i mode is expected to be produced and identified in the redesigned Columbia Linear Machine (CLM). We have developed detailed predictions of the criteria of the onset of the mode and its characteristics in CLM. These are based on significant generalization of previous linear theories[1,2] to include effects of anisotropy in ion temperature gradient,[3,4] collisions and rotation on the mode. We show that collisions have negligible effects, whereas the anisotropy in ion temperature gradient ($\eta_{i\parallel} \neq \eta_{i\perp}$) has a profound effect. A gradient in parallel ion temperature ($\sim \eta_{i\parallel}$) is essential for the instability, whereas a gradient in the transverse ion temperature ($\sim \eta_{i\perp}$) has an indirect effect, which can be either stabilizing or destabilizing. Using the expected parameters of CLM, we have derived the critical values of $\eta_{i\parallel c}$ and $\eta_{i\perp c}$ for the onset of the instability. We have also derived the growth rate and the real frequency as a function of $\eta_{i\parallel}$, $\eta_{i\perp}$, azimuthal mode number m and parallel wave number $k_\parallel$. Exploiting the different roles of $\eta_{i\parallel}$ and $\eta_{i\perp}$, we propose a stabilization scheme of increasing $\eta_{i\perp}$ appropriately for a given $\eta_{i\parallel}$. Lastly, we have included the effect of plasma rotation due to a d.c. radial electric field. For this purpose, we have merged the Rosenbluth-Simon[5] result for a flute type mode due to rotation, with a fully kinetic treatment of a η_i mode with finite parallel wavelength. We show that the centrifugal drive due to a strong rotation and its shear, can have significant effects on the mode stability.

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FURTHER IMPLICATIONS FOR TOKAMAK TRANSPORT FROM THE gBL TRANSPORT FORMALISM*

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The generalized Balescu-Lenard (gBL) collision operator[1,2] provides a unified basis from which neoclassical, turbulent, and ripple transport in tokamaks may be viewed. Here, we consider some further implications of potential significance for tokamak transport using this formalism. In particular, some of these are:

For ripple transport: Contrary to the prevailing lore, arising from the limited context of the original theory[3], trapped particles diffusing due to the "stochastic" ripple mechanism do not in general receive their net radial "kick" per bounce at their banana tips, but rather at some other point on the trajectory. In particular, this expectation is violated for particles precessing rapidly relative to the ripple (e.g., alpha particles). Additionally, the map used to study stochastic transport in earlier work conceals variation of the transport with toroidal precession frequency associated with successive bounce resonances. These have potential implications for attempts to minimize alpha loss by tailoring the ripple from TF coils.

For turbulent transport: The gBL theory predicts an anomalous pinch, of closely related size and scaling to the anomalous diffusion coefficient, which makes the turbulent transport intrinsically ambipolar. The pinch may provide explanations for the observed profile evolution with gas puffing and in some pellet injection experiments, and for the peaking of the impurity distribution near the tokamak center observed in some experiments.

The fact that the particle diffusivity D has been found to be comparable with χ_e in gas puff experiments[4] has been construed as strong evidence that it is electrostatic, rather than magnetic, turbulence which is causing the transport. However, the magnetic transport from turbulence dominated by odd parity modes can also explain such results.

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Particle Simulation of Toroidicity-Induced Drift Modes*

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We have previously investigated the Toroidicity-Induced drift mode using TPC (Toroidal Particle Code)—a fully self consistent, natural coordinate particle code. The simulation employs full dynamics ions and drift electrons; a single mode number $n = 9$ is used in the majority of runs. We have found evidence of a toroidally induced instability, in accordance with the theory, and have determined growth rates, saturation levels, mode structure, and transport information.

Long time spectral analysis of the simulation run reveals a easily recognizable eigenmode structure, with perhaps three dominant frequencies. This occurs despite the existence of a nonlinear saturated state. Radial localization of the eigenmode occurs due to the variation of equilibrium quantities such as ω_e^*; this is manifested in the frequency response by a reduction in strength of the lowest harmonic at large r, and the increase in strength of a third harmonic. Although dominant at descrete frequencies, the spatially averaged spectral density has an envelope shape strikingly similar to that observed in tokamak experiments, with a power law decay $\langle S(\omega) \rangle \sim \omega^{-1}$ for frequencies $\omega_e^* \lesssim \omega \lesssim \omega_{pe}, \Omega_i$. The correlation time, as measured by test particle diffusion, scales much more closely to the envelope half-width ($t_{cor} \sim 1/\Delta\omega$) rather than the individual spectral line widths.

We will also present simulation results of a toroidally confined plasma in the presence of temperature gradients, with $\eta_e = \eta_i = 1$. The application of a new low-noise algorithm to TPC will be discussed, and preliminary test results given, along with plans for future work.

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Scaling Laws for Resistive Turbulence*

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Various systems of reduced MHD equations have been proposed as a basis for the calculation of turbulent transport coefficients. Some of these, from which explicit results have been claimed to follow, may be shown by use of scaling laws to be incapable of representing any transport process at all.

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$Tn\tau_E$ COMPARISONS OF TOKAMAK REACTORS OF DIFFERENT ASPECT RATIOS*

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The $Tn\tau_E$ values of the International Thermonuclear Experimental Reactor (ITER) with an aspect ratio $A = 2.6$, a major radius $R = 5.8$ m, a plasma current $I_p = 22$ MA, and an external toroidal field of $B_{t0} = 5$ T at R; a High Field Experimental Reactor (HFER) with $A = 6.0$, $R = 6.0$ m, $I_p = 8.2$ MA, and $B_{t0} = 12.4$ T; and a Spherical Torus Experimental Reactor (STER) with $A = 1.2$, $R = 1.5$ m, $I_p = 22$ MA, and $B_{t0} = 0.88$ T, are compared using a set of presently popular empirical or semi-empirical confinement scaling expressions. Since these scaling expressions are yet to be based on "first principles" that span the entire range of A, the results of comparison are best suited to helping identify issues critical to furthering our understanding of tokamak confinement.

In the case where the plasma pressure is limited by the Troyon beta scaling using B_{t0}, the Merezhkin-Mukhavatov, Goldston, T-10, and Shimamura-H scaling expressions favor the HFER, while the Odajima-Shimamura, Rebut-Lallia, and Mirnov-like scaling expressions favor the STER. The rest of the scaling expressions (Kaye-Goldston, Kaye-all, Kaye-big, and Asdex-H) suggest comparable $Tn\tau_E$ values. In the case where the plasma pressure is determined by a second stability $\epsilon\beta_p$ limit ($\epsilon = 1/A$), the projections of the T-10, Goldston, Odajima-Shimamura, and Rebut-Lallia scaling expressions are also compared. There it is found that the original I_p in the STER and the HFER would suffice if $\epsilon\beta_p = 0.5$. For the HFER, however, the latter two scaling expressions would require nearly doubling the I_p if the first stability condition ($\beta_p = 1.5$) is imposed.

These varied projections highlight the uncertain I_p, A and R dependencies (or equivalently the apparent dichotomy between the toroidal field and plasma size dependencies and the plasma poloidal flux and magnetic shear dependencies) in tokamak confinement scaling, which are likely to be resolved only by tests at very low and high A. The results also indicate that whether the plasma pressure is determined by a high $\epsilon\beta_p$ limit is critical to the relative viability of the HFER and the STER to ITER, even if the above confinement uncertainties remain.

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Bifurcation Theory of Electrostatic Instabilities*

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The nonlinear states produced by instabilities involving the interaction of a finite number of unstable modes can be studied by analyzing the bifurcating solutions in the unstable manifold. Roughly speaking, by the unstable manifold, we mean the nonlinear extension of the space spanned by the unstable eigenvectors. This approach is illustrated by several elementary examples; in particular, beam plasma instabilities in one-dimensional Vlasov and water-bag models are treated. New solutions corresponding to nonlinear travelling waves, BGK modes, standing waves, and modulated waves are found. The role of the translation and reflection symmetries is emphasized. The calculations provide an illustration of the methods of bifurcation theory.

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MODIFICATIONS OF THE PIES CODE TO ENHANCE CONVERGENCE*

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Modifications have been made to the Princeton Iterative Equilibrium Solver that have increased its robustness. The modifications include using non-flux coordinates to solve for the magnetic field given the current. Part of the current (the perpendicular part) is also calculated in the non-flux coordinates. Flux coordinates are used only to calculate the parallel contribution to the current. Applications to finite beta stellarators without islands will be given. Calculations of finite beta equilibria with islands and stochastic regions are also in progress.

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Electrical Conductivity in Tokamaks Modified by the Ohmic Loop-Voltage*

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In the usual neoclasssical theories, the phase-space boundary between the trapped and passing regions was determined by neglecting the applied Ohmic voltage. In the present work, the trapped-passing boundary modification by the Ohmic loop-voltage is considered and its effect on the toroidal electrical conductivity is examined. It is found that, even though the change in the trapped-passing boundary itself is small, this modification significantly alters the toroidal electrical conductivity values. The new neoclassical electrical conductivity values are about 26 percent closer to the Spitzer values than those from the previous neoclassical theories. A heuristic description of this new physical effect will be discussed, and a rigorous kinetic calculation of the electrical conductivity will also be presented.

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BETA OPTIMIZATION OF IGNITED PLASMAS*

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Beta, ($\beta = 2 \langle p \rangle / B^2$), optimization studies have generally tended to favor broad plasma profiles, since they generally permit the largest plasma currents, and hence the largest betas in accordance with the Troyon-Gruber-Sykes scaling law, β-max = g I/aB, where I is the plasma current in megamps, a the radius in meters and B the vacuum toroidal field in tesla, and g is a coefficient varying between three and four, depending on the assumptions of the study. On the other hand in ignited plasmas, the relevant parameter is the α-power, which is better expressed in terms of $\beta^*(\equiv 2 \langle p^2 \rangle^{1/2}/B^2)$. This measure of the plasma pressure would tend to favor more peaked pressure profiles, and may even permit operation below the conventional Troyon limit. It is therefore useful to review the β-optimization procedures used in tokamak design. This topic is the subject of this paper, and will include consideration of the relationship between β-max and β^*-max for several pressure and current profiles of varying width. The current profile plays an important role in determining the shape of the safety factor, q profile, which in turn affects the ability to support the pressure gradient. It is therefore necessary to assess the two effects, pressure and current profile gradients, simultaneously. The plasma geometry, aspect ratio and cross-sectional shape can also influence the q-profile for a given plasma current. This effect will also be considered. Results for several profiles will be presented for circular and elongated-dee shaped plasmas.

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CAN DYNAMICAL SYSTEMS APPROACH TURBULENCE?

P. Holmes

Sawtooth and other MHD Effects in Tokamaks*

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A three-dimensional nonlinear toroidal full MHD code, *MH3D*, is used to study sawtooth oscillations and other MHD effects in tokamaks.

The profile evolution during the sawtooth crash phase compares well with experiment, but only if neoclassical resistivity is used. (Classical resistivity has been used most of the previous theoretical sawtooth studies.) With neoclassical resistivity, the q value at the axis drops from 1 to about 0.8 before the crash phase, and then resets to 1 through a Kadomtsev type complete reconnection process. This $\Delta q_o \simeq 0.2$ is much larger than $\Delta q_o \simeq 0.01$, which is obtained if classical resistivity is used. The current profile is strongly peaked at the axis with a flat region around the singular surface, and is similar to the Textor profile. To understand this behavior, approximate formulas for the time behavior of current and q values are derived ($q_o(t) = 1 - 2\sqrt{\epsilon_s}(t/\tau_R)^{1/4}$). A functional dependence of sawtooth period scaling is also derived ($\tau_{ST} = \tau_R f(\epsilon_s, \epsilon_\delta, Z_{eff}(\epsilon))$). A semi-empirical scaling is found which fits the experimental data from various tokamaks (τ_{ST} $(\propto \epsilon_s^{-2}\tau_R)$ $\approx 9R^2(T)^{3/2}/Z_{eff}$). Some evidence is presented which indicate that the fast crash time is due to enhanced effective resistivity inside the singular current sheet, generated by e.g., microinstability and electron parallel viscosity with stochastic field line at the x-point.

Low n resistive balooning modes are found to be unstable for Supershot profiles. These modes saturate nonlinearly with a magnetic topology filled with various island structure. At higher β values, some of the islands overlap and produce large stochastic regions. This effect should be taken into account when comparison between theoretical and experimental confinement times are made.

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1989 SHERWOOD THEORY MEETING, SAN ANTONIO

THE THEORY OF NEOCLASSICAL ION TEMPERATURE-GRADIENT-DRIVEN TURBULENCE

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The theory of collisionless fluid ion temperature-gradient-driven turbulence is extended to the collisional banana-plateau regime. Standard sonic η_i-modes are sound waves driven unstable by ∇T_i-induced negative compressibility [i.e., growth rate $\gamma \sim k_{\|}c_s(1+\eta_i)^{1/2}$] with characteristic radial scales determined by the gyroradius [i.e., mode width $\Delta x \sim \rho_s(1+\eta_i)^{1/2}$]. Neoclassical effects modify negative compressibility η_i-modes by:

- introducing parallel viscous damping which makes the long wave length parallel ion flow response dissipative rather than inertial,
- enhancing the linear and nonlinear polarization drifts by a factor of B_t^2/B_p^2.

As a result of these modifications, growth rates become dissipative rather than sonic [i.e., $\gamma \sim k_{\|}^2 c_s^2(\eta_i - 2/3)/\mu_i$, where μ_i is the neoclassical parallel damping rate] and radial mode widths are broadened [$\Delta x \sim \rho_s(B_t/B_p)(1+\eta_i)^{1/2}$]. Neoclassical η_i-modes are fundamentally three-dimensional excitations. Thus, spectral transfer to small scale dissipation occurs, resulting in saturation. Renormalized turbulence theory is used to calculate the ion thermal diffusivity χ_i at saturation. For low k_θ ($\Delta\omega_{k_\theta} < \mu_i$, where $\Delta\omega_{k_\theta}$ is the turbulent decorrelation rate);

$$\chi_i \sim \frac{3\pi}{4}\frac{c_s^2}{\mu_i}\rho_s^4\frac{k_\theta^2}{L_s^2}\frac{B_t^4}{B_p^4}(1+\eta_i)^2(\eta_i - 2/3) \quad \text{for } \eta_i > \eta_{i\text{th}} = 2/3,$$

where k_θ is restricted to $k_\theta\rho_s < \mu_i(L_s/c_s)(B_p/B_t)(\eta_i - 2/3)^{-1/2}(1+\eta_i)^{-1/2}$. For moderate k_θ ($\Delta\omega_{k_\theta} > \mu_i$);

$$\chi_i \sim \mu_i\rho_s^2\frac{B_t^2}{B_p^2}(1+\eta_i) \cong (1+\eta_i)\chi_{i(\text{neoclassical})}.$$

Note in both cases, a strong favorable dependence on B_p (and hence I_p) is exhibited. Furthermore, the χ_i for the long wavelength mode exhibits favorable density scaling. In both cases, $\chi_i > \chi_{i(\text{neoclassical})}$. The possible role of neoclassical ion temperature-gradient-driven modes in edge fluctuations and transport in L-phase discharges will be discussed.

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Current Drive via Plasma Waves with Intrinsic Helicity

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It is well known that toroidal plasmas can be sustained by injection of magnetic helicity. In this report we explore the viability of sustaining plasmas via injection of intrinsic helicity of circularly polarized waves. Although this form of helicity injection has received attention in the past[1,2] there remain fundamental issues to explore. A key point is that the transfer of wave helicity requires that the wave structure be localized transverse to the direction of propagation. A plane circularly polarized wave possesses a finite helicity density, yet it does not transport helicity across surfaces[3]. This property of plane circularly polarized waves is associated with requirements of gauge invariance and the necessity of linkage of the wave magnetic force lines. Wave helicity is closely related to angular momentum. The subtle problems associated with transport of wave helicity also characterize the transport of angular momentum. Here we explore fundamentals of wave helicity injection by investigating the dynamics of a packet of circularly polarized Alfvén waves injected into a semi-infinite magnetized plasma volume. One can view this problem as the conversion of wave helicity, which consists of linkage on the scale of the wavelength, into helicity of the larger scale confining magnetic field, or equivalently as a dynamo where kinetic fluid flow due to the wave packet produces an additional component of the magnetic field. A quasilinear approach to the solution of the induction equation yields the large scale current density $\mathbf{J}(\mathbf{x},t)$ induced by the wave packet as it propagates and is absorbed by the plasma. Relationships between helicity injection, wave helicity, and large scale helicity produced by the induced current density are derived. These relationships indicate that a part of the wave helicity converts to the helicity of the confining magnetic field. Issues concerning self-consistency of the solutions are addressed together with limitations of the quasilinear approach. Extensions of this simple example that suggest conditions for optimal driven current and efficiency are given.

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FAST WAVE CURRENT DRIVE IN LARGE NONCIRCULAR TOKAMAKS - A GLOBAL WAVE CALCULATION*

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Fast wave current drive (FWCD) efficiencies and current profiles are calculated in large, non-circular tokamak geometries using the Oak Ridge ION cyclotron global wave propagation code, ORION. The parallel electric field ($E_{\parallel}$) is treated perturbatively to insure that effects of Landau damping are included as well as transit time magnetic pumping. Results show that the perturbative treatment agrees well with previous calculations in which $E_{\parallel}$ is calculated directly from the wave equation. A phased antenna array of four poloidal current straps spaced toroidally achieves the directivity needed in the launched power spectrum for effective current drive. Results for ITER show an absorbed power spectrum peaked at $n_{\parallel} \sim -2.0$ with a driven current, $I/P_{cd} = -.107$ A/W and a normalized current drive efficiency, $\gamma = .45$ A/Wm^2. Electron absorption and driven current profiles are peaked near the magnetic axis, but total absorption shows a smaller peak off-axis due to resonant ion absorption at the second harmonic of tritium. For a proposed FWCD experiment on Doublet III-D, the power spectrum peaks at $n_{\parallel} = -5.0$ with a driven current $I/P_{cd} \sim -.60$ A/W and $\gamma = .13$ A/Wm^2. Toroidal eigenmodes due to plasma boundaries and reflected waves are more pronounced in this case than in ITER where absorption is more complete.

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Drift Fluctuation Driven Transport and Shear in Tokamaks

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Tokamak electron channel turbulent transport can be determined by assuming a wave spectrum of a given average amplitude and integrating the electron equations of motion. Following this approach Horton, Choi, Yushmanov and Parail [1] find that above a certain amplitude electron transport becomes largely independent of wave amplitude and strongly reduced by shear. Since it is primarily the trapped electrons (which are localized to the outside of the torus) that trap in the wave troughs and are transported, the relevant shear is the local shear in the outer torus which varies strongly as the equilibrium changes. Thus the equilibrium problem should be solved self-consistently as part of a transport calculation.

Equilibrium calculations indicate that as the poloidal beta increases the outer local shear decreases, reducing confinement. At $\beta_p \lesssim 1$ the outer local shear is near zero and transport is quite rapid. This would appear to create a transport barrier in an operating sequence that required increasing poloidal beta.

At sufficiently high poloidal beta the local shear will begin to increase in the reverse direction as is well known from studies of "second stability". This can also give rise to an improved confinement region at sufficiently high poloidal beta and low plasma current. Operation in this region may be attainable using a low current startup sequence that maintains high poloidal beta.

When the electron channel is dominant (and when the electrons are collisionless) we draw the following conclusions: Since the poloidal beta determines equilibrium, power will degrade confinement via increases in poloidal beta and reduction in local shear in the low β_p ($\beta_p \lesssim 1$) regime . In this regime increasing current will improve confinement by reducing the β_p driven shear reduction. In the high β_p regime reducing plasma current will improve confinement. The dependence of confinement on beta and on shear will be illustrated based on equilibrium code (PEST) calculations.

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Electron Temperature Gradient Driven Turbulence and Skin Depth Transport*

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In order to explain the anomalous transport of electrons in tokamaks, we propose a set of reduced nonlinear equations that describe the coupling of linearly unstable short wavelength ρ_e electrostatic fluctuations driven by the electron temperature gradient η_e to the longer wavelength c/ω_{pe} electromagnetic fluctuations. The instability is the toroidal version of the η_e driven lower hybrid drift mode in the presence of the electron temperature gradient emphasized by Guzdar[1] for a slab. The growth rate $\gamma \sim v_e/(r_{Te}R)^{1/2}$ is driven by the local bad curvature and the electron temperature gradient.[2] Since the system of the reduced equations is weakly 3D, with $\nabla_\perp \gg \nabla_{||} = \partial_z - \frac{1}{B}\left[\widetilde{A}_{||}, \quad\right]$, we may consider the possibility of an inverse cascade $\rho_e \rightarrow c/\omega_{pe}$ in the energy spectrum, as in the 2D Navier-Stokes turbulence. Such an inverse cascade may explain the free-energy source of the magnetic fluctuations $\widetilde{A}_{||}$. Previously, such magnetic fluctuations have been assumed, and then used to explain the neo-Alcator type of scaling for χ_e.

The simulations show a finite χ_e in the limit of a flat density gradient ($\eta_e \gg 1$) in contrast to the previously[1] given χ_e. Simplified, large η_e nonlinear equations are derived and solved numerically for the interior H-mode plasma profiles. The anomalous heat flux is composed of an electrostatic convection $q_e = \langle v_x p_e \rangle$ and an electromagnetic component $(v_e/\Delta k_{||})\,\langle \delta B_x^2/B^2 \rangle$. The electrostatic component and the electromagnetic component can be understood from the mixing length theory.

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Neutral Hydrogen Deposition in a Spheromak Plasma. R. M. MAYO AND C. K. CHOI, *Purdue University.*— The importance of neutral particles in the energy confinement of spheromaks has recently been considered[1] as dominating the edge plasma resistivity and representing an energy sink for the hot ion component via charge exchange(CX). Experimental operation often introduces a high density neutral component at the spheromak separatrix. Using this as a boundary condition, we calculate the neutral density profile in one dimension employing the method of Goldston.[2] Results are compared with the transport code ANTIC.[3] Good agreement is observed at small minor radii where $\lambda_{mfp} \ll a$. Predictions for typical plasma conditions indicate that neutral densities at the center of a cold ($T_e \sim 20eV$) spheromak can be as high as 10% while higher temperature ($\sim 100eV$) plasmas can have $1-5\%$ neutrals. The dominant transport mechanism is CX with volume recombination making a negligible contribution. Resultant neutral profiles are found to be strongly dependent on the electron density, but relatively unaffected by edge T_i assumptions.

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BOUNDARY CONDITIONS FOR THE DARWIN MODEL*

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For numerical studies of the wave propagation near an antenna, faraday shield, and conducting boundary, the Darwin model is often used. The Darwin model suppresses propagating electromagnetic waves, but allows other electromagnetic fields to be generated. It is to be expected that the low density plasma near the antenna and shield will be simulated by some particle code and the associated charge and current densities will be taken as sources in Maxwell's equations or in its Darwin model simplification. In most previous uses of the model the calculations were done in all space or in a domain with periodic boundary conditions. In both cases no significant question occurs as to what constitutes correct boundary conditions. For antenna problems and for work near boundaries clearly the boundary conditions are critical. We present several physical and mathematical arguments for our proposed boundary conditions. We also explore the computational complexity of a particle simulation coupled to the Darwin model with our proposed boundary conditions.

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ENERGETIC TRAPPED EFFECTS ON THE INTERNAL KINK MODES*

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The analytical studies of energetic trapped particle effects on the internal kink modes show that if $|\langle\omega_D\rangle/\omega|>>1$ and $(\omega_*/\langle\omega_D\rangle)>0$, the ideal branch is stabilized for $\beta_h > \beta_{h1}$, but a resonant fishbone branch is destabilized with $\omega \lesssim \langle\omega_D\rangle$ for $\beta_h \gtrsim \beta_{h2}$. Since β_{h2} is proportional to hot particle energy, $\beta_{h2} > \beta_{h1}$ for high energy trapped particles. Numerical studies by the NOVA-K code[1], which computes kinetic-MHD stability of realistic numerical tokamak equilibria with neutral beam injection have confirmed these qualitative conclusions, but give quantitatively very different values of β_{h1} and β_{h2} (can be an order of magnitude larger). In addition a necessary condition for exciting the resonant fishbone branch requires that the total plasma $\beta_{c2}>\beta>\beta_{c1}$ where $\beta_{c1,2}$ are the ideal MHD critical β. Therefore, we obtain a stability window in the β - β_h diagram for the n=1 internal kink even in the absence of FLR effects (finite ω_{*i}) of core plasma ions. This is different from the previous analytical studies[2,3] that there is no stability if ω_{*i} = 0. Since the maganetic drift reversal occurs for different flux surfaces and different trapped particle pitch angles, the stability of the internal kink modes must be computed by the NOVA-K code. For alpha particles generated in the ignited tokamaks, the stability of the internal kink modes is weakly influenced because the alpha particle distribution is isotropic in pitch angle and sampling of trapped alpha particles with $\langle\omega_D\rangle$ of different signs almost averages out the alpha contribution to δW. This result is different from the previous conclusion of alpha-particle stabilization of the internal kink obtained[4] from the simple assumption that $\omega_*/\langle\omega_D\rangle > 0$ for all trapped alpha particles.

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Comparison of RF codes: ORION, HYPERION, and SHOOT

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A detailed qualitative and quantitative comparison of three 2D full-wave ICRF codes has begun. ORION is a 2D full-wave finite-difference cylindrical model code with warm-plasma damping. HYPERION is a 2D full-wave poloidal-mode expansion code in flux coordinates with full toroidal geometry described by a sophisticated 3D equilibrium code, but it currently uses only a cold-plasma dispersion relation. Both ORION and HYPERION allow finite E-parallel. SHOOT, the simplest but fastest of the three, is a 2D full-wave poloidal-mode expansion, shooting method code with cylindrical symmetry, warm-plasma damping, and zero E-parallel. To make a quantitative comparison, it is necessary to choose a limiting case where all three of the codes are applicable and approximately the same physics issues are treated (for example, a TFTR-sized, cylindrical tokamak-like plasma with zero E-parallel) and to use a set of input and output units consistent among the three codes. For such a case, we ask what computed quantities are robust and can be meaningfully compared. Quantities of interest are field amplitudes, power deposition contours, heating profiles, total power deposition, and antenna loading. After being assured that the three codes produce comparable results, we can, for example, examine the quantitative effects of toroidicity and finite beta using HYPERION or warm-plasma effects using ORION or SHOOT.

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Theory of High-n Shear Alfvén Gap Mode in Tokamaks*

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High-n toroidicity-induced Alfvén (TAE) gap modes[1] are studied in the $s - \alpha$ space, where $s = (r/q)dq/dr$ is the magnetic shear, and $\alpha = -(2Rq^2/B^2)dp/dr$ is the normalized pressure gradient for tokamak plasmas. In the ballooning mode first stability region, TAE gap modes are found to exist only for α less than some critical value α_c. For $s < 1$, we obtain $\alpha_c = s^2/(1+s)$. We also find that these TAE gap modes reappear in the ballooning mode second stability region within bands of α value. These bands emerge at small shear, $s \leq 0.1$. Full finite Larmor radius (FLR) effects of ions on the TAE gap modes will also be studied.

We apply the WKB method to study the radial structure of the high-n TAE gap modes. In general, bound states exist only if the local eigenfrequency $\omega(r, \theta_k)$ has a maximum in minor radius r, where θ_k is the radial wavenumber of the ballooning representation.

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Bottom Launch for Electron-Cyclotron Current Drive in ITER*

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Previous work, in Refs. 1 and 2 for example, has considered absorption on tail electrons of power injected at the top of a tokamak at frequencies that are downshifted from the cyclotron frequency at the magnetic axis. With the advent of higher-frequency sources, absorption on tail electrons at *upshifted* frequencies becomes possible and is found to be more efficient for driving current in a hot tokamak like ITER. We compare launch from the outside of the tokamak to bottom launch, which has engineering advantages over top launch. Bottom launch leads to absorption on electrons with a narrower energy range, $2T_e < \varepsilon < 3T_e$, which allows modest increases in current-drive efficiency.

We perform Fokker-Planck calculations to estimate current-drive efficiency for the bottom-launch geometry. We include many important effects: relativity, electron trapping, momentum transfer from tail to bulk electrons, and quasilinear tail production. We compare results from the CQL[3] and SMOKE[4] codes. We find that momentum transfer enhances efficiency by more than 50% near the magnetic axis ($r/a < 0.2$) and that efficiency decreases rapidly with increasing r/a. A typical value for the efficiency in a tokamak with $Z_{\mathrm{eff}} = 2.2$ and on-axis temperature $\hat{T}_e = 35\,\mathrm{keV}$ is $\langle n\rangle IR/P \approx 0.2 \times 10^{20}\ \mathrm{A/Wm^2}$.

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Simulation of Dense Z-Pinch Plasmas

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We present results from a simulation of the plasma evolution during the post-ablation phase of a solid deuterium fiber in a dense z-pinch (DZP). Experiments with the NRL DZP[1] have shown the ablated fiber eventually becomes unstable, resulting in neutron pulses of the order of 10^9 per shot. Further, the scaling of total neutron production, N, with total plasma current, I, has been determined to be $N \sim I^{10}$. Past[2] and recent[3,4] analyses of the neutron production mechanism have focussed on the m=0 sausage instability and the accompanying accelerated deuterium beam population, which produces a beam-target interaction quantitatively shown to be a possible mechanism for the observed neutrons. In order to examine this theory in more detail, we are simulating the post ablation and unstable collapse of the fiber plasma with the CIDER[5] hybrid simulation code. CIDER is a $2\frac{1}{2}$-D quasineutral hybrid code with the fields solved in a quasineutral Darwin approximation. The initial conditions for the simulation are taken to be the self-similar state observed numerically by Lindemuth[6] at the end of the fiber ablation phase. We follow the plasma evolution through the unstable m=0 phase and monitor the generated electric fields and the particle dynamics, including distribution functions, densities and temperatures. Our goal is to observe the generation and evolution of accelerated deuterium beams during the column collapse. Results to date of the simulations will be presented and compared with relevant MHD[7] simulations.

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Magnetic Field Diffusion into High Drift Kinetic β Plasma Beams*

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We study magnetic field diffusion into plasma beams using electromagnetic particle-in-cell (PIC) codes. For a plasma beam streaming across magnetic fields with large momentum or energy (high drift kinetic β) we observe good penetration of the beam due to shielding of the magnetic field from the interior of the beam (diamagnetism). We, however, determine that the magnetic field diffuses into the beam on timescales much shorter than classical diffusion times. We also find that the rate of diffusion is larger for smaller electron gyroradius, and that the diffusion rate decreases after the beam has traversed the field for long times. The observation of enhanced magnetic field diffusion is qualitatively in agreement with experimental results (Mishin et al. 1986, Wessel et al. 1988).

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Simulation of RF Driven Plasma Edge*

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Electrostatic computer simulations of a plasma edge driven by an RF electric field in a gap between two conductors (Faraday shields) will be presented. Results show that both the ion flux and the ion impact energies are roughly proportional to the applied power. Both the flux and average impact energy are strong functions of the drive frequency for the wide range of frequencies used, but may vary little over the narrower range of frequencies used in experiments. Ion heating occurs over the entire simulation region implying that waves (ion Bernstein waves) are directly excited at the antenna. Direct observation of these waves will be attempted, and the results will be presented.

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Particle Simulation of Alfven Instabilities in a Neutral-Beam Current-Driven Plasma in a Sheared-Slab Geometry*

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Alfven waves are predicted to be unstable in an ITER plasma in which a neutral beam injection of 1-2 MeV is used to drive the plasma current. One of the major concerns, then, is possible degradation of the current-drive efficiency due to these instabilities. Employing a particle code, MACRO[1], with a sheared-slab geometry, we study linear and nonlinear evolution of these instabilities and their effects on the beam current. Spatial variation of beam density will also be included to investigate radial transport of the beam ions.

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*Work performed for the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48, and supported by Grants-in-Aid by the Ministry of Education, Science, and Culture of Japan

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TOKAMAK TO TOKAMAK VARIATION IN SCALING LAWS*

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Traditionally, tokamak scaling laws are calculated assuming

$$\ell n\, \tau_{e_i} = \vec{\alpha}\, \vec{p}_i + \varepsilon_i$$

where $\vec{p}_i$ contains the logarithms of macroscopic physical quantities such as total plasma current and ε_i is a Gaussian distributed random variable. The scaling coefficients are calculated by minimizing the residual least squares error. An implicit assumption in this procedure is that all tokamaks have the same scaling coefficients, $\vec{\alpha}_k$, where the index k denotes the k-th tokamak. We present the standard statistical test to show that different tokamaks scale differently.

An alternative model is the Swamy random coefficient model where $\alpha_k = \overline{\alpha} + \delta\alpha_k$ where $\delta\alpha_k$ is a random variable. This model significantly alters the error estimates for extrapolation to future devices due to the unknown value of $\delta\alpha$. Results from S. Kaye's global confinement database will be presented. We also find that the current scaling coefficient may depend on device size and ASDEX datapoint have a large influence in determining the aspect ratio scaling.

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Effect of Arbitrary Larmor Radius on Tearing Modes*

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The theory of $m = 1$ and $m \geq 2$ tearing modes for arbitrary large Larmor radius is investigated without using constant ψ approximation. The Larmor radius terms are approximated by a Padé approximant. Analytical results for the collisional, semicollisional, and collisionless tearing modes are presented and discussed. The importance of ion temperature on these modes is elucidated.

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Design Considerations for Advanced Toroidal Experiments

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The purpose of our study is to define a series of necessary but not sufficient conditions for tokamak design viability. These conditions are referred to as robustness parameters. The first parameter concerns changes of solution with respect to changes in current profile [1]. The second parameter concerns a precise regularization technique which we have developed in order to determine parameter regimes of enhanced sensitivity in which severe control problems might arise [2,3]. The third parameter concerns the number of numerical solutions which exist as a function of tokamak design parameters. These conditions are such that we are able to identify questionable tokamak designs for next generation tokamaks.

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

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Tearing Mode Stability of Tokamaks at Finite β

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A gauge invariant, self-adjoint energy principle with a non-vanishing parallel electric field component is used for the study of tearing modes in a finite β tokamak. Near the mode rational surface, it is assumed that the equilibrium is stable to the resistive localized interchange. The inner layer energy can then be modified to extract the "principle tearing mode energy," with the large and small solutions matching smoothly to the outside. Numerical examples of the implementation of this energy principle is presented.

Stability of tearing modes in tokamaks with $q_0 < 1$ and low β_p is studied systematically using this energy principle. We demonstrate that contrary to RFP, where the instabilities are mainly driven by the plasma current, all the reconnection instabilities in tokamaks are of the resonant type. Thus, detailed profile tailoring can modify the tearing mode stability boundary of the tokamaks substantially.

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BALLOONING MODES IN DOUBLE-ADIABATIC AND GUIDING-CENTER PLASMAS IN THE PRESENCE OF ROTATION

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The ballooning stability of axisymmetric plasmas in the presence of rotation has been recently investigated using the ideal MHD model.[1] One of the results in ref. 1 is the identification of a "resonant" instability in the presence of field-aligned flows. The resonance, which occurs when the rotation speed approaches the speed of the slow wave, is also precisely when the equilibrium equation undergoes a transition from ellipticity to hyperbolicity. By formulating the stability problem in the double-adiabatic model, we show that the resonant instability is analogous the the well-known fire-hose instability which too occurs at the transition point of the equilibrium equation. In the presence of purely toroidal and rigid rotation, we find that the anisotropy in plasma pressure can have a potentially stabilizing effect on ballooning modes .

The inadequacy of the ideal MHD and double-adiabatic models in describing the equilibrium and stability of rotating plasmas has been pointed out in refs. 2 and 3. As in refs. 2 and 3, we use the guiding-center plasma (GCP) model. For large - n ballooning modes, we formulate a WKB theory, and contrast the results on stability with the predictions of the ideal MHD and GCP models.

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PLASMA CURRENT DRIVE BY HELICITY INJECTION IN RELAXED STATES

by

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ABSTRACT

The sustainment of plasma discharges (current-drive) using helicity-injection and relaxation is discussed. It is shown that toroidal plasmas may be sustained by applying only poloidal voltage and current. Some of the configurations which can be maintained in this way are calculated.

Abstract for 1989 Sherwood Meeting, April 3-5

THE m=1 INTERNAL KINK MODE IN A TOROIDAL PLASMA WITH AN ARBITRARY q-PROFILE

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An ideal MHD stability analysis of a toroidally, axisymmetric plasma has been performed. The radial eigenfunctions and the growth rate of the mode have been calculated analytically for arbitrary q-profiles, the expression for the growth rate being simple but implicit. We distinguish between regions in the plasma where different approximations hold. In the parts of the plasma where q differs sufficiently from unity, the mode eigenfunction is approximately spatially constant. Integrals over the pressure gradient and the current density in these regions are more important for the stability boundaries than for the actual growth rate of the mode. The growth rate depends sensitively on those parts of the q-profile that are close to unity. The highest growth rates occur if $q \simeq 1$ in an appreciable part of the plasma, since low shear allows for free interchange of field lines. In such cases the mode can be unstable even for zero pressure, when q is above unity in the centre, while, when q is below unity in the centre, the mode is unstable only if the pressure gradient exceeds a threshold. In the latter case the radial displacement function is non-monotonic: the plasma motion is localized in the destabilizing $q \simeq 1$ region and avoids the stabilizing central region.

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Ultra-Fast Numerical Solutions to the Transport Equations using Variational Techniques

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In recent years a number of sophisticated numerical codes have been developed that solve the 1 and 1 1/2 dimensional transport equations in toroidal geometry. These codes have played a major role in the analysis and understanding of data from tokamak experiments. When operated in a relatively simple mode, (i.e. no Fokker-Planck solution, no ray tracing, etc.) such codes typically require 1-3 minutes of Cray CPU time, a sufficiently fast time for many, but not all applications.

The purpose of the present work is to describe a procedure for approximately solving the transport equations on a time scale two orders of magnitude or more faster than existing techniques. Such a procedure would then allow the transport solver to be used as a between-shot diagnostic on existing and future tokamak experiments for the small price, for instance, of a dedicated micro-Vax.

The procedure achieves its high speed by extensive use of variational techniques. A variational principle is derived which determines the time evolution of the quantities $U_j \equiv T_e, T_i, n, n_z, \psi$ or any appropriate subset. The transport coefficients are arbitrary functions of U_j and r and are required only to obey Onsager symmetry. The procedure uses a relatively simple set of trial functions (3 variational parameters/variable) thereby allowing a large part of the calculation to be carried out analytically. The result is a set of first order, ordinary differential equations in time for the variational parameters which can be solved in well under a minute on a micro-Vax.

It should be emphasized that the variational procedure has many, but not all of the options of the full 1 and 1 1/2 dimensional codes. Also, by its very nature it is not as accurate (typically several percent errors) as the "exact" solutions. These are the sacrifices for speed. Several detailed examples and comparisons will be presented at the meeting.

η_e TRANSPORT, DETACHED PLASMAS AND DENSITY LIMITS*

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In a recent paper[1] we studied the thermal equilibria of Ohmic detached plasmas using anomalous transport due to η_e modes and Spitzer resistivity. The safety factor q_D at the edge of the hot detached core was found to decrease to $q_D = 2$ as the density was increased. This density was identified as the density limit since any further increase in density led to a major disruption on TFTR. In the present work we examine the role of neoclassical modification to the Spitzer resistivity in determination of the detached plasma equilibrium and consequently the density limit.

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

EXTENSION OF BRAGINSKII FLUID EQUATIONS TO THE BANANA-PLATEAU REGIME AND APPLICATION TO RESISTIVE INSTABILITIES*

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Neoclassical MHD includes long mean free path effects using similar approximations as the reduced resistive MHD model. When the lowest order components of neoclassical MHD are included in resistive initial value codes, increased growth rates, broadened mode and island widths, lowered thresholds, and altered nonlinear behavior are observed for pressure gradient and tearing instabilities. These effects are expected to be of importance in understanding transport and confinement in high temperature tokamak plasmas.

An alternate approach which will be discussed is to extend Braginskii's fluid equations to the banana-plateau regime without employing the assumptions of neoclassical transport theory. Our equations are therefore more general than neoclassical MHD and its extensions. In particular, the parallel viscosities we obtain are compatible with those of Braginskii. We show that neoclassical MHD and its extension are valid only on the mode rational surface. Because of this constraint, those types of equations are in general not applicable for linear and nonlinear instabilities that have finite radial mode width. We also include temperature gradient terms in the Braginskii viscosities. These go beyond those of neoclassical MHD which includes only temperature gradient terms compatible with neoclassical transport theory. We will apply our equation to the nonlinear evolution of tearing mode, pressure gradient, and ion temperature gradient driven instabilities.

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Nonlocal Energy Transfer Due to Inverse Mode Conversion of Ion Bernstein Waves *

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High power heating of tokamak plasmas by means of ICRF waves is accomplished by launching a long-wavelength wave (the fast magnetosonic wave) using an antenna located on the low magnetic field side of the tokamak. Efficient localized heating results from cyclotron damping and mode conversion into a short wavelength mode: the ion Bernstein mode (IBW). We refer to this process as the direct problem. It is characterized by the absorption and transfer of energy of a large scale wave to a short scale wave in a narrow layer, and has been extensively investigated by several authors. In this study, we consider a full-wave investigation of the inverse process, namely the absorption and mode conversion physics of an IBW that is internally generated in the plasma. The analysis of this problem is of current interest because: i) the mode converted fast wave can be used as a diagnostic of the ion behavior in tokamak experiments, and ii) the conversion of a thermally-generated (or unstable) IBW into a fast wave can cause a non-local transport of energy. Results are presented for the case of a deuterium plasma in which a small fraction of hydrogen ions are present (the case equivalent to fundamental minority heating). Efficient absorption (up to 50%) by the majority ions is observed for minority concentrations below 2% of the electron density. For minority concentrations above 5%, the IBW transfers most of its energy (> 80%) to a fast wave that propagates towards the high field region. Less than 1% of the energy goes into the fast wave that propagates towards the low field region.

*Work sponsored by USDOE

LOW ASPECT RATIO STELLARATOR OPTIMIZATION*

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The design of low aspect ratio stellarators presents the theoretical challenge of reconciling MHD stability with favorable neoclassical transport in a single compact device. Toroidal effects, which are enhanced at low aspect ratios, often tend to influence MHD and transport properties in opposing ways. In this work, a numerical procedure is presented that has been developed to search for optimal low aspect ratio configurations. The parameter space over which the optimization is carried out is defined by a set of Fourier harmonic coefficients describing the boundary of the plasma. By varying this boundary around a tentative design, we can assess the changes in the Mercier stability and the transport of deeply trapped particles in the altered configuration. This forms the basis for a nonlinear optimal search scheme. The success of the procedure depends partly on the selection of an adequate initial configuration; in the present study, the standard large aspect ratio ATF was chosen as the starting configuration. The rapid computations of inverse equilibria, stability, and confinement criteria, are crucial as well. These criteria are evaluated for a set of neighboring configurations to form a figure of merit which is used by the optimization routine to expand the region of exploration in boundary harmonic space toward lower aspect ratios, while maintaining good transport and stability properties.

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Particle Simulations with Predictive Dynamic Load Balancing on Hypercube and Ncube Multiprocessors

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Poisson solution via the conventional FFT algorithm is retarded by the extensive multiple internode communication required on these multiprocessors when the electrostatic field is distributed over a large number of nodes. The alternative solution via direct integration needs less iternode communications. More importantly, it allows greater flexibility in dynamically reallocating the electrostatic grid among the multiprocessor nodes, requires much less internode synchronization, and is known to be espeically simple in one-dimension, even with the inclusion of charge form factors. It was therefore used for our study of various load-balancing algorithms on these machines.

A test case, in which a pulse of half the system width contains half the electrons and ions, has been used to compare these algorithms. Without load balancing this would have an efficiency of 67% relative to a single node, but an efficiency of well above 90% has been achieved with predictive load balancing. This code should also be applicable to the multi-tasking CRAY-2, with similar results.

The code is being extended to higher dimensions, where direct integration is less straightforward, but the benefit of predictive load balancing is expected to remain.

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EQUATIONS OF MOTION IN NON-CANONICAL COORDINATES FOR PARTICLE TRAJECTORIES IN TOROIDAL GEOMETRIES

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We have developed a method for evaluating particle trajectories in toroidal geometries. In this method, particle drift trajectories are evaluated in terms of practical, non-canonical coordinates. In the canonical case, the Hamiltonian is expressed in terms of the canonical coordinates (θ,ϕ), conjugate momenta (P_θ,P_ϕ), and time t. Hamilton's equations of motion then give $d\bar{X}/dt$, where $\bar{X}=(\theta,\phi,P_\theta,P_\phi,H)$. For practical purposes, it is desirable to have equations of motion for the non-canonical coordinates $(\theta,\phi,v_\|,\chi,t)$. We have developed a method for obtaining the equations of motion in this practical non-canonical coordintes. These equations have a number of advantages, which include: magnetic fields of arbitrary complexity can be handled easily, particle drift orbits in any toroidal device can be studied, and correctness of calculations can be ascertained using two independent checks on rate of change of Hamiltonian in numerical calculation of orbits. We apply this method to evaluate particle trajectories in the tokamak and RFP. This work is supported by DOE and LANL HBCU program.

SYNCHROTRON RADIATION IN FUSION POWER REACTORS

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Synchrotron radiation (SR) has been discussed mainly as a power loss mechanism which may endanger ignited operation of advanced fuels. In contrast, in D-T fusion plasma evaluations SR is mainly considered for its flattening effect on temperature profiles, with otherwise marginal impact on the overall energy balance. This, however, was based on the expected achievement of high wall reflectivity and the resulting high probability for reabsorption of the radiation in the plasma. The recent consideration of ceramic materials for the first wall, characterized by low reflectivity coefficients for synchrotron radiation, may well enhance the importance of the synchrotron power exhaust channel even for D-T fueled reactors.

More recently, beneficial implications of SR have been discussed in the context of advanced fuel plasmas burning at high temperature. One is the potential use of SR as a mechanism for passive current drive which may be a very attractive alternative to other active methods such as EC, IC, NB. The other one is the potential of direct conversion of this radiative power at high efficiency.

In this paper the radiative power losses from D-T and advanced fuel plasmas, as well as the fraction of SR which can be made available for special purposes, is assessed as a function of the reflectivity of first wall materials, of the field configuration, of density profiles and of operating parameters. The evaluation is based on a numerical code SYLO which includes - beside of the usual simplifying assumptions - several features of interest such as mode conversion at the reflecting wall. For the homogeneous case, a scaling law for synchrotron radiation power loss has been derived from results obtained by SYLO which differes considerably from the ones found in the literature.

The various calculational procedures and fit formulae which are available are used to evaluate and compare the impact of synchrotron radiation on the energy balance in different D-T and D-3He reactor schemes including field reversed configurations.

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Modern Software Documentation: A New WEB system for Fortran, Rational Fortran, and C

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With the advent of modern computerized typesetting systems such as TEX, sophisticated, user-friendly software documentation becomes feasible. Knuth's WEB documentation system for Pascal has been previously rewritten for the C language by S. Levy. Fortran presents a more difficult challenge because of its line-oriented input format and a complicated syntax. Here, building on Levy's work, I describe a new WEB capable of simultaneously handling Fortran, Rational Fortran (RATFOR), and C code. WEB consists of two programs: WEAVE, which uses the full power of TEX to produce the documentation (for example, this abstract) and TANGLE, which strips off the documentation and produces compilable files. Features include automatic formatting and typesetting of the code, the ability to introduce blocks of code in a logical rather than a functional order, a built-in macro processor, and an extremely useful index of all variables as well as additional topics specified by the user. Output of a sample (nonsense) program follows. This work was supported by U.S.D.o.E. Contract No. DE AC02 76CHO3073.

1. Each function or scrap of code can be introduced by arbitrary TEX text. The scraps can be grouped into logical blocks, which are written out (tangled) in compilable form. The powerful macro processor is C-like.

#define N 100 /* The macros apply to all languages. */
#define $MM(min, max)$ $(max - min + 1)$ /* A macro definition with arguments. */

⟨Main program 0⟩^{C} /* Languages can be mixed. */
⟨Functions 3⟩^{F}

2. Fragments of code can be introduced and discussed before (or after) they are used. (One can accrete to a fragment later, as logic demands. TANGLE will combine fragments with identical names, then write them out together.) As an example, common blocks can be defined once, then included with each function. Maintaining a separate include file is unnecessary.

⟨Common 2⟩^{F} ≡
  real $a(0:N)$, $b(MM(-5,5))$; /* The macros are expanded by TANGLE. */
  common /*arrays*/ a, b; /* Spacing is inserted automatically. */

This code is used in section 3.

3. Block/loop numbers are inserted automatically to help the user. Indenting is automatic. The semicolons are inserted automatically (and stripped off by TANGLE). Constructions such as `.le.` are automatically converted to more familiar mathematical symbols. Code fragments can be intermixed with text, as in $c =$ `'character␣string'`.

⟨Functions 3⟩^{F} ≡
  subroutine $f(x, y)$; /* Reserved words are in boldface. */

  ⟨Common 2⟩^{F}; /* This module is inserted in the proper place by TANGLE. */

  if $(x \le y)$ **then**; /* L1 */
    $x = 3.14159 \cdot 10^{-9}$D; /* A new double-precision value for π. (Note use of TEX's math mode inside comments.) */
  else; /* L1 */
    do $i = 1, 5$; /* L2 */
      $x = x$^y; /* Exponentiation. */
    end do; /* L2 */
  end if; /* L1 */

  end;

This code is used in section 1.

4. An very useful index is provided. Underlining indicates the module number in which the variable is defined. One-character variable names such as i are not included unless they are defined explicitly in the code.

Sherwood Meeting, April 3-5, 1989
San Antonio, Texas

MHD Analysis of Peaked Density Profiles Produced by Pellet Injection in JET*

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After pellet injection during some JET discharges a very fast time scale instability causes an abrupt collapse of the central electron and ion temperature.[1] High toroidal mode number (n) MHD stability has been investigated by Galvao, et al.[2] and these discharges found to be ballooning unstable. The work reported here (presented also in Ref. 3) has focused on low n stability. Equilibria were generated using pressure profiles which bracketed that used in Ref. 2 for the unstable discharge. Safety factor (q) profiles were used which had q_0 (q at the magnetic axis) equal to 1.5 (within the error bars for q taken from the polarimetry data). All profiles used gave instability to an "infernal" mode[4] with $n = 2$ and an energetically dominant poloidal wave number (m) equal to 3. This mode is stable for values of q_0 slightly (± 0.1) above or below 1.5. The $n = 2$ nature of the instability is consistent with measured MHD activity for the discharge considered and $m = 3$ is consistent with measured post-instability electron temperature contours for similar discharges. The $m = 3$ experimental pattern is also consistent with cylindrical nonlinear calculations for an $m/n = 3/2$ infernal mode instability.[5] The size of the growth rates found ($\gamma\tau_{\rm HP} \simeq 0.005$) indicate the mode is just above marginal stability. The above establishes the infernal mode instability as a strong candidate for the experimental temperature collapse. Details of the above together with additional results will be presented.

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COHERENT STRUCTURES AND HEAT TRANSPORT IN ION PRESSURE GRADIENT DRIVEN TURBULENCE

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The nonlinear evolution of toroidally driven η_i modes has been simulated by means of a spectral code in the local approximation. The pressure gradient evolution is treated self consistently.

The investigation has been especially focused on the dependence of the anomalous heat flux on forcing and dissipation.

It is found that the formation of insulating coherent structures may lead to significant reduction of the heat flux with respect to the mixing length estimates.

CALCULATION OF HAMADA COORDINATES AND ITS APPLICATION IN THE MOMENT EQUATION APPROACH TO NEOCLASSICAL TRANSPORT THEORY FOR A LARGE-ASPECT-RATIO TOKAMAK

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The moment equation approach to neoclassical transport theory introduced by Hirshman[1] in the study of impurity transport for axisymmetric toroidal systems seems to be an adequate frame to: (1) unify the treatment of different collisional regimes; (2) to include several effects like external sources, viscosity and ambipolarity, and (3) to analyze phenomena like induced plasma rotation and current drive. Due to its completeness this approach has also been extended to nonaxisymmetric toroidal configurations.[2,3] However the constrain to use Hamada coordinates, and the difficulty to calculate them has significantly limited the analitical application of this approach. In this work we present the calculation of Hamada coordinates $\{V, \chi, \varsigma\}$ for the simplest tokamak model

$$\vec{B} = B_o[\Theta(r)\hat{\theta} + \hat{\phi}]/(1 + \frac{r}{R_o} cos\,\theta).$$

The transformation to Hamada coordinates turn out to be

$$\begin{aligned} V &= 2\pi^2 r^2 R_o \\ \chi &= \frac{1}{2\pi}(\theta + \frac{r}{R_o} sin\,\theta) \\ \varsigma &= \frac{1}{2\pi}\left[\varphi + \left(\frac{r}{R_o\Theta}\right)\left(\theta + \frac{r}{R_o} sin\,\theta - I(r,\theta)\right)\right] \end{aligned}$$

where $I = \int_o^\theta (1 + \frac{r}{R_o} cos\,\theta)^{-1} d\theta$. The contravariant components of $\mathbf{B}$ are $B^V = 0$, $B^\chi = \Theta B_o/2\pi r$ and $B^\varsigma = B_o/2\pi R_o$, and the jacobian is taken equal to one.

The knowledge of this Hamada set allows us the comparision of the results of the moment equation approach against well known results. We find for example that the Pfirsch-Schlüter diffusion coefficient is correctly reproduced. Other questions regarding the ambipolar electric field in tokamaks and the effect of momentum sources on it can also be addressed.

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THE BETA LIMIT IN ATF
DUE TO LOCAL IDEAL MHD INSTABILITIES

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The marginal pressure profile that is imposed either by ideal ballooning or interchange modes on every nested flux surface of a 3D equilibrium that models the ATF device is determined for conditions of vanishing net toroidal plasma current. The corresponding limiting values are β = 3.75 % and β (0) = 9.89 %. Mercier modes dominate in regions of strong stellarator-like magnetic shear and nonsymmetric ballooning modes dominate in regions with strong tokamak-like magnetic shear.

SHERWOOD THEORY MEETING 1989

Self-Organization in Sheared Drift-Wave Turbulence*

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We investigate turbulent drift-wave dynamics in a sheared magnetic field using direct numerical simulations. The model is two-fluid electrostatic fluctuations in a 2-D sheared slab. Departure from an adiabatic electron response is allowed. The free energy source is the externally maintained density gradient. Local driving (trapped electrons, toroidicity, etc.) can be employed to sustain a saturated state. Sinks are collisional current dissipation and absorption of outgoing sound waves. Density fluctuations are nonadiabatic in a region within $\Delta_D \equiv (\omega_* \nu_e)^{1/2}/k'_{\|} V_e$ of the resonant surface. In this hydrodynamic layer the decoupling of potential and density fluctuations and the loss of shear-induced dissipation allows the density fluctuations to self-organize and replaces the Hasegawa-Mima inverse energy cascade with a direct one. The organization occurs through chaining of Δ_D-sized blobs (themselves transient) into large-scale structures, leading to strong, sustained extraction and thus controlling the system energetics. Within the hydrodynamic layer the direct density cascade causes most of this energy to go into collisional dissipation, in marked contrast to the balance in an adiabatic system. The result is that for subcritical driving levels (no linearly unstable modes) the nonadiabatic system supports much higher saturated fluctuation levels than the adiabatic, even though *linear* nonadiabatic waves are the weaker. Thus, current models of drift-wave-induced tokamak edge turbulence may be strongly underestimating particle transport levels.

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Sherwood Theory Meeting
San Antonio, Texas
April 3-5, 1989

TRANSPORT IN A TOKAMAK BASED ON THE BRAGINSKII MODEL*

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In an earlier paper, Z. Naturforsch. 42a, 1101-1114 (1987), we have laid out the general procedure for the analysis of tokamak transport based on the two-fluid transport model of Braginskii for electrons and ions. In order to obtain explicit, but approximate results, to compare with experimental observations, we approximate our system to represent a large aspect ratio, near circular cross section tokamak. We present explicit equations for the time evolution of the basic profile functions.

We also explore the underlying validity of the Braginskii model by considering moment approximations to the electron and ion Boltzmann equations, as was done many years earlier by Kolodner and by Herdan and Liley. We find that a thirteen moment approximation leads to a Braginskii-like system. Higher moment approximations are considered, but lead to extremely complex fluid approximations.

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Abstract for 1989 Sherwood Meeting

ENERGY TRANSPORT IN JET AND COMPARISON WITH THEORY

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Comparison between the measured and theoretically predicted energy transport has frequently been based on comparison of the global confinement times, or the corresponding average thermal conductivity. A proper test of a theoretical model, however, requires comparison of the predicted and measured local energy fluxes. The experimental energy fluxes have been derived with reasonable accuracy using the JET energy balance analysis code. The variation in the measured flux profiles between different operating conditions will be illustrated and, where available, its variation with global parameters. This will be compared with various predictions based on trapped electron and η_i instabilities, ergodic magnetic fields, or empirical transport laws.

The observed propagation of the heat pulse following a sawtooth crash, and other transient events, provides an independent measure of energy transport.

A possible explanation of the difference between the thermal diffusivity deduced from this propagation, and from steady state confinement, is the presence of an inward non-diffusive heat flow. Evidence for such a flow will be examined. Wave damping mechanisms which are not dependent on spatial gradients, such as Landau damping, could give rise to such an energy flow.

Some of the evidence from all sources for and against the different transport mechanisms will be summarised.

BROADENING OF THE LOWER HYBRID $N_{\parallel}$ SPECTRUM BY TOROIDAL EFFECTS

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Toroidal geometry affects the evolution of the parallel wavevector $k_{\parallel}$ along the lower hybrid wave trajectory.

In this paper the broadening of the launched spectrum is investigated both analytically and numerically.

Possible scenarios for filling the gap between the high parallel phase velocity of the injected waves and the electron thermal velocity are discussed.

A simple analytic expression is derived for the upshift factor and compared with the prediction of a ray tracing code for several experimental situations.

Hybrid (Particle-Fluid) Simulations of Low Frequency Plasma Microinstabilities*

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We have developed a new type of hybrid simulation technique.[1] In the traditional scheme[2] the collisional, small Larmor radius electrons are treated as a fluid, and the ions are treated as particles. Our work is prompted by the widespread use of fluid-ion models to study low frequency plasma microinstabilities.[3] The ion momentum equation is reduced in the approximation that frequencies are smaller than the ion cyclotron frequency. When combined with the quasineutrality condition, this gives rise to a vorticity equation which expresses the balance between parallel flow of charge along the field lines, and the perpendicular polarization charge drift. The electrons are treated as particles in the collisionless drift kinetic approximation. In shearless slab geometry the particles perform $\mathbf{E} \times \mathbf{B}$ drifts perpendicular to the magnetic field and retain full dynamics in the parallel direction. At the moment the model has been implemented in the two-dimensional, electrostatic, shearless slab approximation.

This is the first computational fluid model to self-consistently incorporate the effect of the wave-instability fields on the orbits of the particles. We have used the model to study the relative importance of the ion polarization nonlinearity and the $\mathbf{v}_E n$ nonlinearity in the context of the universal drift-wave instability. Also, we are conducting work on the influence of kinetic electrons on the saturation mechanisms for ion-temperature-gradient driven instabilities, and on interchange instabilities. In particular, the role of the power transfer terms $\left\langle j_{\|}^{i} E_{\|} \right\rangle$ and $\left\langle j_{\|}^{e} E_{\|} \right\rangle$ emphasized by Hong and Horton at this meeting will be analyzed. This will be assessed by comparison of results from fluid models to those obtained with our hybrid model.

1. P.M. Lyster and J-N. Leboeuf, IFS Report #357, (1989) (submitted to J. Comput. Phys.); H. Okuda, Space Science Reviews **47**, 41 (1985).

2. J.A. Byers, B.I. Cohen, W.C. Condit, and J.D. Hansen, J. Comput. Phys. **27**, 363 (1978).

3. See for example G.S. Lee and P.H. Diamond, Phys. Fluids **29**, 3291 (1986).

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

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LBL–26725a

SHERWOOD THEORY MEETING
San Antonio, Texas, April 3–5, 1989

Studies in ICRF Heating: (A) Explict Solutions for Minority Heating*; (B) Scattering of a Magnetosonic Wave by Density Turbulence†

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(a) We present a completely analytic theory of ICRF gyroresonant heating and mode conversion in one dimensional slab geometry. Three cases are examined: non-degenerate minority resonance (e.g., D-He^3), second harmonic resonance [1], and degenerate resonance (e.g., D-H). Explicit expressions are derived for the coefficients of transmission, reflection, conversion (magnetosonic to ion Bernstein wave), and absorption, and for the absorption profile (one for each species in the degenerate case). (The distribution in $v_{\|}$ is allowed to be non-Maxwellian.)

The crucial idea [1] is that gyroresonant absorption is interpreted as mode conversion to a continuum of Case-van Kampen modes propagating in $\underline{k}$-space.

(b) A fast magnetosonic wave, launched into a tokamak plasma, scatters off turbulent density fluctuations in the plasma edge. We calculate the angular distribution of the scattered wave using cold fluid theory. We first assume all wavevectors to be perpendicular to the magnetic field for the incident wave, the turbulent density fluctuations, and the scattered waves. We find that the scattering is mostly perpendicular to the incident wave vector. The treatment for finite $k_{\|}$ is in progress. Our goal is to calculate the fraction of incident ICRF wave energy transmitted to the gyroresonant region.

[1] H. Ye and A. N. Kaufman, *Phys. Rev. Lett.* **61**, 2762 (1988)

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†Work supported in part by US DOE Magnetic Fusion Science Fellowship, administered through Oak Ridge Associated Universities

NONLINEAR SOLUTION BRANCHES OF REDUCED MHD EQUATIONS

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We study "saturated" MHD instabilities in terms of stable non-linear solution branches of weakly dissipative MHD equations. Starting from our recently proposed exact representation of MHD by scalar functions, we derive reduced MHD equations for helically symmetric cylindrical geometry and for toroidal geometry, including resistivity, parallel and perpendicular heat conductivity, and viscosity. Using given external sources (mass, heat, electric field) and appropriate boundary conditions, we find equilibrium solutions and nonlinear solution branches corresponding to kink, quasi-interchange and tearing instabilities. We describe two particular cases :

a) - A helically symmetric cylindrical plasma possessing an equilibrium with flat current profile, from which solution branches of the kink type (helical equilibria) and branches of quasi-interchange type (stationary convective states) bifurcate.

b) - A toroidal plasma possessing an axisymmetric equilibrium from which stationary solution branches of the internal kink type bifurcate. The latter case is discussed in relation to the problem of sawtooth oscillations with $m = 1$ precursor in tokamaks.

PARAMETRIC DECAY OF LOWER HYBRID WAVES IN TOKAMAK PLASMAS

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Parametric instabilities during lower hybrid waves injection are studied by solving the parametric dispersion relation in a wide range of frequencies.

In fact for typical tokamak plasma parameters the instability can be driven by non-linear coupling of ion-acoustic or ion-cyclotron damped modes.

Moreover wave depletion due to finite extent of the pump is considered by solving the set of non-linear coupled equations for the wave amplitudes.

In the numerical calculation the parameters of lower hybrid current-drive on ASDEX at 2,45 GHz are taken into account. As result one can say that this kind of phenomena can be responsible of the modification of the characteristic of the launched spectrum.

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*Student

Annual Controlled Fusion Theory Conference (International Sherwood Theory Meeting), San Antonio, TX, April 3-5, 1989.

PLASMA PHYSICS CONSIDERATIONS IN THE FUSION IGNITION EXPERIMENT IGNITEX

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A fusion ignition experiment (IGNITEX) is described, the original concept for which was proposed by Rosenbluth, Weldon, and Woodson[1] on the basis of Coppi's idea[2] of a compact ignition experiment and recent technology advances in pulsed power high current systems. In this concept a single-turn-coil tokamak device produces a self-sustained fusion reaction of the type T(d,n)α. The basic idea is to employ a very high magnetic field and a very high plasma current to heat the plasma ohmically to thermonuclear temperatures and then to produce a stable ignited plasma. In this paper the preliminary analysis of various plasma physics aspects that describe the fusion ignition experiment is presented, including: thermal energy balance at ignition, simulations of the plasma evolution throughout the discharge, plasma equilibrium and stability, transport and plasma-wall interaction, alpha-particle kinetics and transport, plasma thermal runaway during the ignited phase of the discharge, alpha-induced modes and confinement degradation, and electron cyclotron radiation transport. The experiment will permit the scientific study of a new regime of physics: alpha-heated ignited plasma.

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Sherwood Theory Conference
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A Lagrangian Method for Collisional Equations*

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A technique is described for treating an integral collisional term in a kinetic equation in the framework of particle schemes. The consistency of the method with the original integro-differential equation is based on the relation between particle schemes and quadrature formulas for the computation of an integral on the irregular grid of the particles.

A numerical scheme has been derived, which uses a triangulation on the particle grid at each time step. The result is compared with the exact solution in a two dimensional case.

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1989 SHERWOOD THEORY CONFERENCE
ANNUAL CONTROLLED FUSION THEORY CONFERENCE
SAN ANTONIO, TEXAS

APRIL 3 – 5, 1989

Strong Impurity Transport in Rotating Tokamak Plasma Including Temperature Variations*

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Previously[1], a strong impurity ordering that assumes $\delta_{pi} Z^2 \frac{\nu_i}{\omega_{ti}} \sim 1$ (where $\delta_{pi} = \frac{\rho_{pi}}{L}$, Z the impurity charge, and ω_{ti} the ion transit frequency) was adopted for evaluating the impurity transport in rotating ($v_{thZ} < V < v_{thi}$) tokamak plasmas. Although the temperatures were set to be constant, it was found that a strong up-down asymmetric density variation $\frac{\tilde{n}(\theta)}{\bar{n}} \sim O(\epsilon)$ (where ϵ is the inverse aspect ratio) can be induced by the nonvanishing parallel friction. Note that the up-down density variation is essential for radial transport. Here, we extend the previous work to include the temperature variations, which enhances the up-down density variation in the flux surface (and therefore the radial transport) via the thermal friction[2]. In addition, the radial heat flux is calculated. It is found that the inclusion of the temperature variations does not qualitatively alter the impurity transport.

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Sherwood Meeting, April 3-5, 1989

San Antonio, Texas

Nonlinear Interaction of Resistive Modes for $q < 1$ in Tokamaks*

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Tokamak experimental measurements of $q < 1$ in the plasma core are now quite common, in some cases immediately following a sawtooth crash. Such q profiles can be unstable to resonant tearing modes having poloidal and toroidal mode numbers satisfying $m/n < 1$, as well as to the resistive $m = n = 1$ mode. It has been suggested that the nonlinear interaction of these unstable modes may be responsible for the crash. We consider the nonlinear evolution of resistive modes in toroidal geometry for monotonically increasing safety factor profiles with q_0 in the range 0.6 to 1.0. The evolution of the independent resonant instabilities, each specified by a toroidal mode number n for $m/n < 1$, indicates typical resistive tearing mode growth to large saturated magnetic islands, and for $m = n = 1$ the evolution leads to full reconnection with $q \geq 1$ everywhere. Calculations for single unstable modes indicate, for chosen profiles, that strong magnetic island overlap and hence nonlinear interaction should occur for the full evolution. Initial calculations prove this to be the case, although the details of the evolution are sensitive to the mode selection and initialization. We exploit this sensitivity to understand the roles played by the various modes to influence the observed dynamics.

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A Theory of Microwave-Produced Potentials in Plasmas - The Pleiade Experiments Revisited

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Microwave power incident on a plasma existent in a magnetic field with a longitudinal gradient can cause the development of a localized potential if the microwave frequency corresponds to the local value of the electron cyclotron frequency at some surface within the region. Local heating of electrons passing through the resonance leads to a sudden increase in their magnetic moment, thus to a tendency to expel them from that region. Countering this tendency is ion inertia and the requirement for quasi-neutrality. Thus, depending on the particular circumstances, the situation described can lead to the development of a localized positive potential well, one sufficient to electrostatically confine the electrons, while accelerating the escape of ions. A classic example of this process is provided by experiments conducted in France in the early 1960's by Consoli and his co-workers, exemplified by those performed on the "Pleiade" facility[1]. A remarkable feature of these experiments was the generation (both steady-state and transient) of accelerated ions having an energy spectrum with both an extremely sharply-rising low energy edge and a quite narrow width, bespeaking the generation and expulsion of ions from an extended region of nearly constant positive plasma potential, i.e., from a "square well". A theory will be described that seems to explain both the mechanism of generation of this potential well and its detailed shape, thus accounting for the observed ion-energy spectrum. The theory self-consistently takes into account the combined magnetic and electrostatic forces acting on the electrons and on the ions that lead to the observed effects. The value of a careful theoretical reexamination of these old experiments is that similar phenomena may occur in modern experiments, for example ones using microwave power to provide electron heating, current drive, or enhanced longitudinal confinement, as in the tandem mirror or its variants.

*Work performed under the auspices of the U.S. D.O.E. by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

1. R. Bardet, T. Consoli, and R. Geller, Physics Ltrs. 10, 67, (1964)

MHD Modeling of the Fueling of a Tokamak Reactor by Compact Toroids*

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We investigate the feasibility of fueling a tokamak reactor through the injection of compact toroids (CT's). Such a technique is believed to be necessary in order for the fuel to adequately penetrate[1]. Of critical importance is the rate at which the CT tilts and reconnects with the tokamak field.

As a simplifying measure, we assume that the CT is placed at rest in a uniform magnetic field modified to exclude the CT and model the subsequent evolution of the fluid and field variables using the three-dimensional nonlinear resistive initial-value code TEMCO[2]. Preliminary calculations show the CT tilting 90 degrees in about an Alfven time (relative to the CT) with reconnection occurring during the tilt. Results to date are presented.

[1] L.J. Perkins, S.K. Ho and J.H. Hammer, Nucl. Fusion 28, 1365 (1988)
[2] A.A. Mirin, Comput. in Phys. 2, 62 (1988)

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

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ALPHA PARTICLE DIAGNOSTICS USING LASER SCATTERING TECHNIQUES*

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Laser scattering off of thermal fluctuations in a burning plasma can be a useful diagnostic for determining alpha particle characteristics. In this work we show that electromagnetic corrections to the standard electrostatic scattering theories are always important except for CO_2 scattering systems. We also show that scattering off of thermal field fluctuations is important at lower frequencies and dominates the usual scattering off of electron density fluctuations for relevant parameter regimes. It is very difficult to resolve alpha particle properties from field fluctuation scattering as electrons dominate all ionic contributions unless the magnetic field anisotropies can be used to advantage. Highly focused CO_2 systems scattering results need to include the important broadening caused by finite electron transit times through the laser beam.

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GYROVISCOUS TREATMENT OF STABILITY IN A FIELD REVERSED CONFIGURATION*

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Previously a variational approach has been developed to describe the stability of a multifluid flowing plasma.[1] This treatment has now been generalized to include the gyroviscosity. For the reduced case of a one-fluid nonflowing gyroviscous plasma, the dispersion relation is

$$\omega^2 + \Omega_G \, \omega + \gamma_{MHD}^2 = 0 \; ;$$

the "middle" term represents the effect of gyroviscosity. This equation is reminiscent of the two-fluid effect[1] which also led to a middle term.

The theory has been applied to the internal tilt instability of a field reversed configuration (FRC). The difficulty of a singular gyroviscous term at the O-point is accommodated in a pragmatic way by requiring that the trial function satisfy a regularity condition at the O-point. Early results predict stability if $a/(c/\omega_{pi}) > C\, b/a$, where a is the separatrix radius, and b is the separatrix half-length (b/a is the elongation). This is the same scaling as for the two-fluid effect[1] with the important difference that here the constant of proportionality, C, is about twice as large.

The gyroviscous theory is essentially a fluid-based description of perpendicular kinetics. As such it offers a simple quasi-analytic representation of one phenomenon contained in a more complete kinetic treatment, such as the Vlasov model. Its simplicity allows trends (e.g. the scaling of the marginal stability boundary) to be found more easily than by Vlasov fluid computations. The possibility of treating the parallel ion kinetics using the parallel viscosity in a fluid model is also being investigated.

*This work supported by USDOE Contract No. DE-AC06-80ER53098, and by a Grant-in-Aid from the Japanese Ministry of Education.

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LINEAR 3D IDEAL MHD GLOBAL INTERNAL MODE STABILITY ANALYSIS WITH THE *TERPSICHORE* CODE

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The ideal magnetohydrodynamic (MHD) stability analysis of three dimensional (3D) toroidal configurations has been limited so far to the stellarator expansion method [1]. This method is only valid for systems with a relatively large aspect ratio, with a planar magnetic axis and with a toroidal magnetic field that is much larger than the helical and poloidal fields. Therefore, it cannot be applied to analyze the stability properties of configurations, like the Helias stellarators or the JET Tokamak with its large internal helical magnetic structures.

The fully 3D MHD stability code *TERPSICHORE* has been developed to examine arbitrary 3D configurations with nested flux surfaces. In its present version, the code is limited to the investigation of global internal mode structures. A new Fourier technique is used to map 3D toroidal equilibria obtained with the VMEC code [2] to Boozer magnetic flux coordinates. For marginal stability studies, the incompressibility constraint is imposed to reduce the components of the displacement vector in the energy principle from three to two. These components are then Fourier analyzed in the two periodic angular variables and finite hybrid elements are employed for the radial discretization. The problem reduces to a special block penta-diagonal matrix eigenvalue system solved by inverse vector iteration. Applications to various configurations will be presented.

[1] J.M. Greene and J.L. Johnson, Phys. Fluids 4 (1961) 875.
[2] S.P. Hirshman, W.I. Van Rij, and P. Merkel, Comput. Phys. Comm. 43 (1986) 143.

Matrix Solvers for 3D Ideal MHD Equilibrium and Stability Calculations*

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We consider the analysis of 3D toroidal plasma configurations possessing nested flux surfaces (no islands). In many models, one employs angle-like coordinates to map positions on each flux tube. The use of finite Fourier series in the angle coordinates together with finite elements in the radial coordinate leads to matrix problems in which the operators have block multi-diagonal forms and in which the blocks are dense. For the equilibrium problem, one must solve a nonlinear matrix system in which the operator is block tridiagonal. A Picard iteration or a modified Newton's method can be employed. For the stability problem, one obtains a linear matrix eigenvalue problem which has a mixed tridiagonal and pentadiagonal form. It is solved by combining eigenvalue shifts with the method of inverse vector-iteration. Sylvestor's theorem is used to insure we do not miss important (i.e. negative) eigenvalues. These matrix systems are typically very large requiring Cray-2 memory capabilities. By using either the PAMS or PAMERA solvers (employing BLAS 3 type matrix routines) we attain efficient computation speeds close to the maximum possible. These methods have been used in the construction of our stability code, TERPSICHORE, and have other potential applications in plasma physics and beyond.

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Transport Timescale Simulation of ITER Operating Scenarios *

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We have simulated complete, fully-ignited shots for both the Physics Phase (R_0 = 5.8 m, a = 2.2 m, I_p = 22 MA, B_{T0} = 5.0 T) and Technology Phase (R_0 = 5.5 m, a = 1.8 m, I_p = 18 MA, B_{T0} = 5.3 T) of the proposed International Thermonuclear Experimental Reactor (ITER) using the Tokamak Simulation Code (TSC). [1] Our results include complete PF coil current scenarios, resistive flux consumption during current ramp-up, plasma heating, burn and shutdown, and the auxiliary power required to reach ignition.

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

[1] S. C. Jardin, N. Pomphrey and J. DeLucia, J. Comp. Phys. 66, 481-597 (1986).

Dynamical Study of Axisymmetric Stability in Alcator C-Mod†

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The Tokamak Simulation Code (TSC)[1] is used to investigate the positional stability of Alcator C-Mod plasmas. This code provides a time-dependant, non-linear description of the axisymmetric MHD and transport behavior of a tokamak plasma, a well as its electromagnetic coupling to the external circuits including the passive vacuum vessel structure. It is verified that the nominal equilibria with an elongation 1.8 are passively stabilized on the ideal MHD time scale. On the resistive diffusion time scale, vertical stability is controlled by an active feedback system that modifies the voltage applied to a pair of poloidal field coils in response to the poloidal flux difference between two observation loops. Different instability growth (or decay) rates are obtained be varying the gain coefficients in the PDI feedback law. By turning off the active feedback system, the passive, resistive wall instability growth rate is obtained. The latter is compared with the predictions of a multifilament circuit model code and a linear MHD code.[2]

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

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[2]S. W. Haney, M.I.T. report PFC-RR-88-12 (1988)

STABILITY BETA LIMIT OF LOCAL MODES FOR THE TJ-II FLEXIBLE HELIAC

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Local stability properties with respect to Mercier and ballooning modes for the TJ-II flexible heliac[1] to be built at the CIEMAT site, are studied using the 3-D equilibrium code VMEC[2]. Given the high flexibility of the TJ-II device, i.e., changing the hard core currents the rotational transform per period can be changed from .16 to .78. This leads to several configurations with different magnetic well depth and rotational transform which are being investigated[3]. In this paper the influence of the magnetic well depth and the pressure profile upon stability are particularly emphasized. Magnetic configurations stable to Mercier modes with an average beta in excess of 4% are presented.

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†Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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SHERWOOD THEORY MEETING 1989

Bounds on Instability Growth Rates in Tokamaks*

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A previously derived upper bound on growth constants is applied to the tokamak. The simplest form of the bound gives a limit

$$\gamma < \frac{\omega_{pi}}{\sqrt{\varepsilon}} \frac{u}{v_i},$$

where u is a speed such that nue is the current density, and ε is a certain dielectric constant. For a dielectric constant $\varepsilon \geq (k^2 \lambda_{Di}^2)^{-1}$ appropriate to low-frequency drift waves, this bound becomes

$$\gamma < \omega_* \left(\frac{B}{B_\theta} \frac{1}{\beta_\theta} \right),$$

where B is the toroidal field and B_θ and β_θ are the poloidal field and poloidal beta. This is the growth constant for the collisionless trapped particle mode multiplied by a factor greater than unity. Refinements to include collisions and other effects are in progress.

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Thermoelectric Currents in the Scrape-off Layer of Diverted Tokamaks

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Asymmetries in the power deposition to the target plates of a divertor produce different sheath temperatures and sheath potentials at the plates. Since the divertor plates are grounded in present experiments, a thermoelectric current is induced in the scrape-off layer along magnetic field lines connecting two sheath regions with differing potentials. Such currents have been observed on JET [1]. The scrape-off layer currents can modify the collisional transport across the separatrix [2]. External biasing of the divertor plates could thus be used in order to control transport near the plasma edge. It is therefore of interest to calculate the current produced by divertor plate biasing. In this poster a model of the scrape-off layer of a diverted tokamak plasma is used to compute the current into the divertor plates. Both thermoelectric and external sources are included. The model allows the calculation of the current if the bias potential and power flux at both plates, the ion saturation curent at the colder plate, and the midplane temperature are known.

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

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TF-RIPPLED EQUILIBRIUM FOR ITER*

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Stochastic loss of fast alpha particles from a TF-rippled tokamak reactor may be excessive.[1,2] This loss is associated with the size of the magnetic ripple, $\delta(R, Z) = (B_x - B_n)/(B_x + B_n)$. Here, B designates the magnitude of the magnetic field. The subscripts "x" and "n" denote the maximum and minimum values of B as one moves toroidally for fixed major radius (R) and displacement from the toroidal midplane (Z). If the ripple exceeds a critical value, the stochastic diffusion of fast alphas increases abruptly. Therefore, the spatial variation of the magnetic field ripple is important.

Present models of the rippled tokamak plasma need improvement. Linear superposition of the vacuum ripple on an axisymmetric equilibrium has been used.[3] Reiman and Johnson found that a fixed-boundary rippled equilibrium magnifies the ripple because the plasma current follows the rippled field lines.[4] We will discuss results for free-boundary 3D equilibria, using VMEC.[5] Key parameters include the ripple inside the plasma, bulging of the plasma boundary, and finite pressure effects.

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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COIL REALIZATION FOR LOW ASPECT RATIO STELLARATORS*

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Stellarators can be designed by changing the shape of the last closed flux surface so that certain "goodness" criteria are maximized. (See the poster by Morris et al.). The question then, is whether such optimized configurations can be produced by a set of real(izeable) coils.

Using the NESCOIL code,[1] the last closed flux surface may be surrounded by any periodic toroidal surface, and the current distribution on this surface can be found that will create the desired last closed flux surface. The surface current can then be cut apart into discrete coils.

For the coil designer, there are many opportunities for clever optimization of the results:

- The current lines can be closed poloidally or helically.
- The shape of the winding surface can be varied to
  - maximize the plasma to coil spacing
  - minimize the coil kinkiness
  - maximize access
- Coils may be created on one surface, a few removed as discrete coils, and the remaining fields can be created from coils on a different surface.

Using these techniques, we have synthesized coil sets for several low aspect ratio ($A_p = 3 - 5$) configurations. Results of these studies will be presented.

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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SHERWOOD THEORY MEETING 1989

Physics Scaling of D-T Reactor Plasmas*

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The plasma parameters of a steady-state D-T fusion reactor are narrowly defined by the technical constraints of power flux through the first wall together with blanket and shield thicknesses. Present figures lead to a plasma minor radius of 2–3 m, plasma density 1–2$10^{20}$m^{-3} and mean temperature 10 keV. Such a plasma will give a power flux of 3–10 MW/m^2 through the first wall. For the tokamak case the geometric factors of elongation, safety factor, and aspect ratio are also narrowly defined as about 2, 2, and 4, respectively. As discussed by Kadomtsev, and by Connor and Taylor, plasma physics behavior must be a function of four variables, β, G, C, and D, where

$\beta \propto nT/B^2$	plasma beta
$G \propto T/(BL)^2$	(ratio of gyroradius to plasma size)^2
$C \propto n/\left(T^{3/2}B\right)$	ratio of collision to gyrofrequencies
$D \propto T/\left(L^2 n\right)$	(ratio of Debye length to plasma size)^2

With the full four parameters n, T, L, and B and four dimensionless variables, strict scaling is not possible. However, if we can discard one variable as probably unimportant then we can consider scaling keeping three variables constant. We discard D, the Debye distance term. Then $L \propto \left(\beta^{1/5}C^{-1/5}G^{-1/2}\right)B^{-4/5}$, $n \propto \left(\beta^{3/5}C^{2/5}\right)B^{8/5}$, $T \propto \left(\beta^{2/5}C^{-2/5}\right)B^{2/5}$, while $D \propto G\beta^{-3/5}C^{-2/5}B^{2/5}$.

A fourth parameter F, the ratio between fusion power and losses, describes nuclear reactions which are not plasma physics phenomena and therefore are not conserved by constant β, C, and G. Approximately $F \propto nT\tau$ and since $\tau \propto B^{-1}$, $F \propto nT/B \propto (\beta B)$.

We can now scale from reactor parameters a realistic set, (RR), corresponding to slightly improved L-mode confinement and Troyon β-limit, and an optimistic set, (OR), with a four-fold improvement in β and a two-fold improvement in confinement. Tabulating the results gives

	B(T)	a(m)	I(MA)	$n\,(10^{20}\text{m}^{-3})$	T(keV)	F
Reactor RR	6	2.5	20	1.5	10	1.0
	20	0.95	25	10.3	16	3.3
Reactor OR	3	2.5	10	1.5	10	1.0
	20	0.54	14	31.0	21	6.7

One conclusion is that to simulate the reactor plasma physics correctly the high field machine should operate at higher temperature. Values of β, C, G, and D from present experiments will be discussed together with the resulting confinement scaling.

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Natural Elongation, an Old Fashioned MHD Problem

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Numerically computed free boundary tokamak equilibria with any given set of poloidal field (PF) coils have shown that the shape of the plasma cross–section tends to become elongated as the inverse aspect ratio $\epsilon \equiv a/R_0$ increases. This is the phenomenon of "natural elongation". It is of great practical importance in the design of tokamak experiments in that configurations whose cross–sections are similar to the naturally elongated shapes are quite robust against current or position perturbations in the PF coils. Equally important, such configurations tend to minimize the magnetic energy required for the PF and TF (toroidal field) systems.

The purpose of the present research is to carry out an "old fashioned" MHD calculation, and analytically derive the properties of naturally elongated tokamaks. In particular, the elongation and triangularity are calculated as a function of inverse aspect ratio, poloidal beta β_p, and surface safety factor q_a. The critical feature of the analysis is the assumption that the externally applied vacuum field consists of a pure vertical field $B_V \mathbf{e}_Z$. This source represents the lowest order multipole contribution from a set of discrete PF coils. Indeed, if the PF coils are located outside the TF magnet, the vertical field is the dominant field contribution in the vicinity of the plasma. In the context of this analysis, natural elongation is thereby defined as the elongation of the free boundary plasma cross–section from an externally applied pure vertical field.

The calculation shows that the elongation scales as $(\kappa - 1) = \epsilon^2 f(\beta_p, q_a)$ and the triangularity as $\delta = \epsilon^3 g(\beta_p, q_a)$. The functions f and g are obtained by solving the Grad–Shafranov equation up to and including third order in ϵ. The vacuum solution is evaluated using Green's theorem. Matching the tangential magnetic fields across the plasma–vacuum boundary provides the conditions for determining f and g. Specific results are presented for the case where the pressure and current are characterized by Bennett–like profiles. In this case the entire calculation is essentially analytic. The results from the theory are compared with those from a numerical code that solves the "exact" free boundary problem (*i.e.* no expansions in ϵ or β).

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Decay of Long Time Correlations in Hamiltonian systems

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Understanding the long time behavior of Hamiltonian systems is extremely important for calculation of transport processes, especially since phase space generically contains a mixed structure of regular (stable resonances) and irregular (stochastic) regions. In case of two degree of freedom systems (area-preserving maps), it has been shown that the resonant islands trap a stochastic orbit for long periods and cause the correlation function to decay more slowly than t^{-1}, implying that a statistical description of transport as diffusive is inappropriate.[1,2]

It is still an open question whether the transport in the stochastic region of higher degree of freedom systems is normally diffusive. We examine the decay of correlation functions and the momentum diffusion tensor for a four dimensional mapping which can be derived from a three degree of freedom Hamiltonian. Our numerical results suggest that the trapping effect of islands might not be as serious as in the two degree of freedom case. This is quite plausible since when there are more than two degrees of freedom, trapped orbits can escape from one resonance region to another through the mechanism of the Arnol'd diffusion.

We derive corrections to the quasilinear diffusion tensor as a series in correlations by using the characteristic function method.[2] A summation of a selected, infinite set of terms in this series (the principal terms) gives results which fit computations extremely well for moderately large nonlinearity. The theoretical and numerical results both approach the quasilinear limit as the nonlinearity becomes larger.

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Equilibrium of a Plasma in the Fluid and Kinetic Theory*

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The derivation of equilibrium plasma profiles using the fluid or kinetic models is discussed. The kinetic solutions (the density, the temperature, the current, and the self-consistent magnetic field) were recently obtained by solving the Vlasov-Maxwell system.[1] When the Vlasov equation is replaced by the equilibrium fluid equation, $\mathbf{j} \times \mathbf{B} = c\nabla p$, it is shown that the fluid description, with only the inclusion of the density gradient, is equivalent to the kinetic treatment. However, when the temperature gradient is also taken into account, the fluid description seems to become inadequate. The ∇p, which includes the density and temperature gradients, is unable to provide a complete system such that the individual density and temperature profiles can be obtained. The more realistic situations (with density and temperature gradients) pertinent to current laboratory plasmas, are thus better described by the Vlasov-Maxwell system. We illustrate these by considering two examples representing a simple z-pinch (current in the axial direction) and a simple tokamak (current in both the axis and azimuthal directions).

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

ECH DEPOSITION PROFILES IN TJ-II WITH A NON-MAXWELLIAN ELECTRON TAIL

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A new absorption module has been added to the ray–tracing code RAYS developed at Oak Ridge National Laboratory[1], that permits to calculate the one-pass microwave power absorbed when a non–maxwellian electron distribution function is present in the target plasma.
The current carrying distribution function is simulated using a bi–maxwellian sheme, $f_e=\mu f_b+(1-\mu)f_t$, with three independent parameters, tail temperature, drift velocity and tail population , able to reproduce experimental conditions. A weakly relativistic dielectric tensor has been calculated analytically[2] and has been used for the absorption module.
Results are presented for the TJ-II configuration for first (f=28GHz.) and second (53.2GHz.) harmonic heating. A comparison with the pure maxwellian case is also presented.

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Transport of high power 140 and 250 ghz radiation from an FEL waveguide up to and through the entrance of the Microwave Tokamak Experiment.

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We describe the design of a 6 mirror system for transporting high power radiation (2–3 gw at 140 ghz, 8–12gw at 250 ghz) 30 meters from the FEL source to the entrance of the Microwave Tokamak Experiment (MTX) at Lawrence Livermore National Laboratory. The design is started using a gaussian optics code and iterated by calculating beam spillover and diffraction at the mirrors and apertures with the code MTH, a discretized evaluation of Huygen's scalar integral for the diffracted field. The side lobes that radiate from the FEL rectangular waveguide TE_{01} mode are fully clipped, in partial stages at each of the first three mirrors, J0,J1, and M1. The design uses independently varying focal lengths for the E and H planes for J0 and the fourth mirror M2 (mirrors J1 and M1 are flat) to obtain a round spot at M2 and a beam at the 5th mirror M3 with a round spot and equal radii of curvature. M3 and M4 then can use equal f_E and f_H. Our actual design for M4 has $f_H >> f_E$ to elongate the spot at the duct entrance in the H plane. The design of M2 requires special consideration since it not only produces a 90^o bend of the beam, as do all of the mirrors, but also has an additional 39^o rotation of the outgoing beam about the incoming beam's axis, with the result that not only is $f_E \neq f_H$ but also neither the E nor H plane is aligned with the 90^o bending plane. This requires rotation of the principal axes of the mirror M2 about its normal in order to cancel quadratic cross terms in the mirror curvature. Cubic correction terms on all mirrors are ignored since they are calculated to be sufficiently small. Scattered beam power at M4 and the MTX duct make diagnostic measurements more difficult. Careful consideration must be given to the placement of absorbers on the walls in these areas. Tradeoffs of two 140 ghz designs identical from J0 through M2 are described. Case one (two) diffracts less (more) on M4 but more (less) on the duct entrance, has a slightly smaller (larger) edge field at the duct exit, and is predicted to have 10% less (more) power absorbed in the plasma. About 10% of the incident FEL power is calculated to be lost to the clipped sidelobes at the first three mirrors, with only an additional $1-2\%$ lost to the rest of the transport system. Transport through the 22 cm long duct is done by decomposing the field at the duct entrance into a set of waveguide modes. The relative phase slip of the modes through the duct then creates a large wall field at the duct exit, roughly 0.5 of the peak entrance field. Further transport of this exit field to the plasma location, 18 cm further, then generates new side lobe patterns. Future upgrades considered are MTX duct inserts, smooth or corrugated, possibly tapered. These offer the possibility of reduced fields at the duct wall and greater beam divergence and phase variation across the narrow (toroidal) direction to further increase the plasma nonlinear absorption. Diffraction losses and duct wall fields should be reduced at 250 ghz.

Particle-in-cell Simulations of Electron Heating by Upper Hybrid Waves Using the Massively Parallel Processor*

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Simulations of electron heating by upper hybrid waves have been conducted using the MPPPIC code, a 2-1/2 dimensional electrostatic particle-in-cell code developed for the Massively Parallel Processor (MPP) at NASA Goddard Space Flight Center. The MPP consists of 16,384 processors configured in a 128 X 128 array with nearest-neighbor communications. Although the MPP has a slow clock and I/O speeds, MPPPIC is as fast as the corresponding PIC code on a CRAY X-MP. The simulations assume a cold electron ring distribution with a loss cone in a background of cold electrons. The simulations indicate that the electron ring distribution excites upper hybrid waves with a large growth rate. During the saturation stage, the background electrons are heated perpendicularly and the electrons of the ring distribution just outside the loss cone are heated perferentially to higher energies. The role played by upper hybrid waves in heating the electrons are discussed. A video will illustrate the simulation results.

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SPATIAL EFFECTS ON THE IGNITION AND BURN OF D-^{3}He MIXTURES

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Previous work [1] has shown that the ignition of D-^{3}He mixtures may be possible in a tight aspect ratio, high field toroidal geometry, under conditions somewhat more favorable than those required for D-T ignition. Time-dependent, radial simulation showed that consideration of the spatial geometry is required to understand the physics of ignition and burn. Near burning conditions, the plasma divides naturally into two regions, a central fusion burning region and an outer region at lower temperature where thermal losses due to conduction and radiation dominate. In the central region the net energy source is the excess of fusion heating over the bremsstrahlung and synchrotron radiation losses, all of which are governed by the intrinsic plasma properties rather than external application. Global parameters such as the energy and particle confinement times do not adequately describe the burning region and cannot be extrapolated from present day experiments in a straightforward manner. In this work we discuss these questions and also consider the effects of finite beta on the equilibrium and stability of such configurations.

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

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Mercier Stability Criterion with Plasma Flows *

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Recent interest in the ballooning mode stability criteron for plasmas with mass flows has motivated us to reconsider the Mercier criterion which, in the presence of flows, is not known whether it imposes a more severe condition for plasma stability. Toroidal and poloidal flows supported by the ideal magnetohydrodynamic equations are included in the formalism in generalizing the usual Mercier stability criterion. It should be pointed out that an earlier attempt of generalization has yielded incorrect results.[1]

As suggested by the ballooning mode analysis in the presence of flows,[2] the Mercier criterion is analyzed in a toroidally rotating frame of reference, and derived by a δW energy principle. It is shown that plasma flow in the direction of the magnetic field does not necessarily destabilize the plasma. It is seen that the Mercier criterion can also be derived from a condition on the solution of the Euler–Lagrange equation for the ballooning mode and that ballooning modes impose a more severe condition for plasma stability.

*Supported by U.S. DOE grant DE-FG02-86ER53223.

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Sherwood Theory Meeting 1989

Drift-Rippling Theory of Edge Turbulent Transport*

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We present an improved theory of edge turbulence which is based on a drift-rippling mode system. This analysis contains attributes of the well known density gradient and temperature gradient driven turbulence models. Unlike our previous theory of edge turbulent transport[1], the inclusion of the density equation dynamics allows a proper treatment of particle transport. Furthermore, effects due to the presence of the diamagnetic drift frequency on the nonlinear saturation are included. From a practical point of view, this complete theory of edge turbulent transport includes important alterations due to ionization effects and particle sources with recycling (as well as impurity radiation enhancement[2]). In light of the ASDEX IOC mode[3], where this improved confinement regime is critically dependent on recycling, the advantage of our approach is clear. Modifications due to neoclassical effects[4] are also given. Preliminary results from a simplified drift-rippling system include: transport enhancement and altered transport scalings (weaker decrease with temperature and mode number). Analytic results will be presented for nonlinear saturation levels and transport coefficients. Numerical results will also be presented for a 3D nonlinear fluid code[5] which is applied using specifics of the TEXT tokamak.

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Impurity-Driven Drift Waves in the Reversed Field Pinch*

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Reversed Field Pinch plasmas are known to contain a low level of high-Z impurities. These impurities drift relative to the background plasma because of the presence of the applied toroidal electric field and because of diamagnetic drifts that differ from such plasma-ion drifts. Although these relative drifts are small, it is shown that they can induce low-frequency long-wavelength dissipative drift instabilities in a plasma with transport processes.

Initial results are given just for the un-magnetized plasma (or for plane waves propagating along a magnetic field), using only electron thermal conduction as the plasma transport process. For this example, a marginal stability condition is identified which proves to be independent of wavelength and dissipation rate. The instability is found to persist at all dissipation rates, and, in fact, the growth rate saturates at short wavelengths.

In its present form, this slowly-growing electrostatic instability may be relevant to next generation RFP devices with discharge times lasting more than a few hundred milliseconds. Future work will include oblique propagation in sheared magnetic fields, and additional transport processes in the plasma, as well as a finite temperature of the impurity particles.

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Extension of Fluid Moment Descriptions To Include Kinetic Effects*

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Fluid moment descriptions of plasmas (ideal MHD, resistive MHD) have proven to be very useful in developing models of toroidal plasmas. The underlying density and momentum conservation equations neglect the effects of the stress tensor $\underline{\underline{\Pi}}$. This approximation is valid for a collisional tokamak plasma in the Pfirsch-Schlüter collisionality regime. However, in the physically relevant banana-plateau regime the viscous stresses within a magnetic flux surface ($\underline{\underline{\Pi}}_{\parallel}$) are significant and lead to neoclassical transport.[1] Also, together with the gyroviscous stresses ($\underline{\underline{\Pi}}_{x}$) they lead to the neoclassical MHD fluid description[2] of tokamak plasmas.

In this work we take this line of development one step further. Namely, we utilize the same basic density and momentum moment equation approach to describe kinetic instabilities (e.g., drift wave instabilities). This is done by calculating the stress tensor $\underline{\underline{\Pi}}$ from a kinetically derived distribution function. The equations so derived are then closed not by determining $\underline{\underline{\Pi}}$ in terms of the lower moments n and $\underline{V}$, but rather by the specification of $\underline{\underline{\Pi}}$ in terms of the potential fluctuations $\tilde{\phi}$ in the plasma. Thus, for example, for a linearized, collisionless perturbation in a sheared slab model $\underline{\underline{\Pi}}$ is proportional to $(\omega\text{-}\omega_*)\,(e\tilde{\phi}/T_e)$ and a combination of the plasma dispersion function of argument $\omega/k_{\parallel}v_T$ and its derivative. Collisionless drift waves with adiabatic electrons, fluid ions ($v_{Ti} << \omega/k_{\parallel} << v_{Te}$, $k_{\perp}\rho_i << 1$) and Landau damping (or growth) can thus be derived from this model. Also, collisional and turbulent diffusion effects can be readily added in the kinetic determination of the distribution function and thus in the consequent $\underline{\underline{\Pi}}$ and effects on a "fluidlike" description of the plasma. The advantages of including the kinetic effects through $\underline{\underline{\Pi}}$ instead of the usual procedure are: 1) the equations so derived more directly extend the very useful ideal, resistive and neoclassical MHD equations into kinetic regimes; 2) in the "equilibrium" limit the equations reduce to the classical Braginskii and neoclassical transport equations[1,3] (including the neoclassical Ohm's law with trapped-particle and bootstrap current effects); and 3) the time evolution of density, plasma flows and currents become explicit parts of the calculations.

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Effects of Particle Transport on Sustained Ignition in the ITER Design*

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Dilution of reacting species by build up of helium ash and its effect on ignition in the ITER tokamak have been studied in a series of simulations with the one-dimensional BALDUR transport code.

Thermal diffusivities in these simulations were scaled from JET values[1] and particle transport was controlled by $D = A \times \chi_e/7$ where A was varied from 1 to 16. Recycling of deuterium and tritium was set to .998 while the helium ash recycling was varied from 0.5 to 1.0. The simulations thus far indicate that helium particle transport is a critical issue for sustained ignition.

These simulations are optimistic in that only 10% radiation and no sawtooth effects have been included. More realistic modelling results will be presented which include 30% core radiation. as well as sawteeth and the effects of a simple two-point divertor model[2].

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MHD FLUCTUATION LEVEL AND TRANSPORT IN REVERSED FIELD PINCH

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MHD fluctuation level in RFP plasma is reduced from a simple model that MHD relaxation and sustainment of RFP configuration are caused by the reconnection of lines of magnetic field driven by (m=0, n=1) mode nonlinearly excited by multi m=1 internal kink modes. Then the lines of magnetic forces becomes stochastic by the MHD fluctuations and the energy transport of such a RFP plasma is studied.

Time average of Ohm's law is expressed by

$$\eta \langle \underline{j} \rangle = \langle \underline{E} \rangle + \langle \underline{v} \rangle \times \langle \underline{B} \rangle + \langle \tilde{\underline{v}} \times \tilde{\underline{B}} \rangle \tag{1}$$

where $\langle \underline{v} \rangle$ is the time average and $\tilde{\underline{v}}$ is the fluctuating part. When we think that the toroidal flux regeneration is caused by the driven reconnection of (m=0, n=1) mode and compensates the resistive dissipation of the flux in steady state, the θ component of Eq.(1) is given by

$$\eta \langle j_\theta \rangle \approx \langle \tilde{v}_z \cdot \tilde{B}_r \rangle \tag{2}$$

since $\langle E_\theta \rangle = 0$ and $\langle v_r \rangle = 0$ in steady state. Then we have

$$\tilde{B}_r / B_\theta \approx 2\,\Theta\,\eta / (\mu_0 a \tilde{v}_z) = 2\,\theta a / (\tau_R \tilde{v}_z) \tag{3}$$

where τ_R is resistive diffusion time and Θ is the pinch parameter.[1] The order of $\tilde{v}_z$ is $R\gamma$ and γ^{-1} is the characteristic time of the current peaking and γ is around the growth rate of tearing instability. Then the MHD fluctuation level is reduced to

$$\tilde{B}_r / B_\theta \approx 2A'\,\theta\,(a/R) S^{-0.5-\alpha} \tag{4}$$

where $A' = O(1)$ and α is small number ($\alpha \lesssim 1/6$).

The diffusion coefficients of electron and ion of RFP plasma with MHD turbulence are given by[2]

$$D_e = \pi R v_{Te} |\tilde{B}_r / B_\theta|^2, \quad D_i = \pi R v_{Ti} |\tilde{B}_r / B_\theta|^2$$

and then the effective diffusion coefficient of ambipolar diffusion is

$$D \approx \pi R v_s |B_r / B_\theta|^2 \tag{5}$$

where v_{Te}, v_{Ti} are their thermal velocities and v_s is the sound velocity. When we assume that thermal diffusion coefficient D_χ is A" time of D (A" O(1)), then D_χ and the energy confinement time τ_E are given by

$$D_\chi = A'' \pi R v_s |\tilde{B}_r / B_\theta|^2 = A \pi R v_s (2\theta a/R)^2 / S^{1+2\alpha} \tag{6}$$

$$\tau_E \sim 1.4 \times 10^{-3} A^{-1} (R / a\theta^2)\, \tau_R / (S^{2\alpha} \beta_\theta^{1/2}) \tag{7}$$

where β_θ is the average poloidal beta value. When RFP plasma is sustained by ohmic heating only, Eq.(7) reduces $\beta_\theta \sim 0.5/(A^{2/3} S^{4/3})$, which is consistent with the experimental results.

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Non-Local 1-D Kinetic Stability of FRC.* P. Papanikolaou, H. R. Lewis,† and C. K. Choi, School of Nuclear Engineering, Purdue Univ. -- Local approximation is often used to explain anomalous transport in an FRC, e.g., to model LHD waves near the separatrix. The local approximation, however, fails for an FRC because of the existence of sharp gradients in the equilibrium plasma. A code to study the non-local 1-D kinetic stability of FRC is being developed using a general formalism[1] for non-homogeneous Vlasov equilibrium. The goal of this calculation will be the generation of the eigenvalue and eigenfunctions which characterize 1-D stability for an FRC. The state of the computation and work in progress will be discussed.

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*Work supported by the U.S. DOE

†Office of Fusion Energy, DOE

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ACCESS TO THE SECOND STABILITY REGIME IN THE PBX-M TOKAMAK*

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We demonstrate that the existing PBX-M device should be capable of operating in the second-region of stability with $\beta > 12\%$. Complete shot simulations are performed using TSC with the Coppi-Tang transport model, neo-classical resistivity, neutral beam heating and current drive, bootstrap current, and a sawtoothing model. The evolution of the plasma shape and the current penetration is calculated self-consistently. By continuously monitoring the ballooning mode stability of all surfaces, we are able to show that there exist discharges which are stable at all times as the plasma evolves from a low current, low beta circular shape to a high current, high beta bean shaped cross section. A fast current ramp, bean shaping, and profile peaking due to pellet injection are all essential ingredients in this totally stable sequence. Examination of time slice equilibrium with the CAMINO code enables us to view the trajectories of the surfaces in the S-α/Ψ stability space.

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Abstract for 1989 Sherwood Meeting

FISHBONES AND SAWTOOTH STABILISATION IN THE KINETIC BULK ION REGIME

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Present high temperature experiments, such as JET, are approaching the conditions where the stability of m=1 modes is modified by bulk ion kinetic effects, as their mean gyroradius ρ_i can be of the order of the width of the transition layer at the q=1 surface, $r=r_o$. These effects are in general destabilising [1]. Energetic particles, such as fusion produced α-particles in an igniting plasma, also affect the stability of m=1 modes causing fishbone oscillations and/or sawtooth stabilisation [2].

We show that, in the large gyroradius regime, purely oscillatory m = 1 modes can be found in the absence of energetic ions and of resistivity, for values of β_p below the mhd stability threshold β_p^{mhd}. These modes do not rely on the effect of the bulk ion diamagnetic frequency ω_{di}. When the energetic ions are included, the branch with frequency $\omega_{di}/2 < \omega < (\omega_{di}^2 + \omega_A^2 \rho_i^2/2r_o^2)^{1/2}$ is resonantly destabilised ($\omega_A = v_A/\sqrt{3}\, R_o$).

Thus we find that it is possible to excite fishbone oscillations, with frequencies not determined by the mean magnetic drift frequency $\bar{\omega}_{Dh}$ of the trapped energetic ions, even when $\beta_p < \beta_p^{mhd}$, extending the instability domain obtained by the fluid bulk ion theory [3]. In addition, these oscillations are suppressed for values of the poloidal beta β_{ph} of the energetic ions larger than those found in the fluid bulk ion limit [4] by an amount

$$\delta\beta_{ph} \sim (s_o/\epsilon_o^{3/2})(\rho_i/r_o),$$

where $s \equiv (d\,\ell n\, q/d\,\ell n\, r)$, $s_o \equiv s(r_o)$ and $\epsilon_o \equiv r_o/R_o$, consistently with the numerical results in [5]. A window of stability against m = 1 modes persists provided $(\rho_i/r_o) < (\bar{\omega}_{Dh}/2\omega_A)$, i.e. $T_{io}/(3.5\text{MeV}) < 0.1 s_o^{-1} \beta_{io}^{1/2})$, with $\beta_{io} = 8\pi n T_{io}/B^2$ and $T_{io} = T_i(r_o)$, a condition that is easily satisfied for the proposed ignition experiments.

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DC-HELICITY INJECTION IN AN RFP

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The effect of dc-helicity injection in an RFP is being studied using a 3D MHD code in cylindrical geometry. This research is motivated by the results of our earlier investigation on RFPs with nonideal boundaries[1]. It was found that interruption of current flow along field lines by material boundaries leads to surface helicity leakage and destabilization of current-driven modes. The resultant enhanced fluctuation, through the induced $\mathbf{v} \times \mathbf{b}$ electric field, self-consistently transports helicity to the surface. Thus, reversing the flow of helicity through the boundary via dc-helicity injection may be effective in controlling the level of dynamo activity and resistive shell instabilities. This may provide an important experimental tool in understanding the effect of the dynamo on RFP confinement. In addition, finding ways to stabilize the resistive shell instabilities is of great practical importance.

The code configuration consists of an RFP with a poloidal field divertor. Current sources are placed where the magnetic fields enter and exit the plasma boundary. The amount of dc-helicity injected is then calculated self-consistently. The boundary consists of a thin resistive shell, which is itself surrounded by an outer perfectly conducting wall; a vacuum region separates the resistive shell and conducting wall. The code can also examine the effectiveness of current drive using dc-helicity injection in tokamaks.

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THERMALLY DRIVEN MAGNETIC EDGE TURBULENCE

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The temperaure gradient semi-collisional microtearing mode has been considered as a model for magnetic fluctuations in the tokamak edge. As a model, it is attractive because the scaling of the magnetic fluctuation level with respect to temperature gradient and magnetic shear is consistent with general observed trends in confinement scaling[1]. Because the mode is inherently feeble, consideration of effects which introduce additional sources of free energy is desirable. One possibility, previously examined in the context of the rippling mode, arises from impurity radiation[2]. The simplest model allowing consideration of radiation effects occurs in the limit $\beta_e(L_s/L_T)^2 >> 1$, where coupled temperature and magnetic fluctuations are localized by the thermal conductivity. In this limit, renormalized one-point and two-point equations are derived and presented. The saturated magnetic fluctuation level is found by mixing length and eigenmode solution of the one-point equations. Relaxation of the constraint $\beta_e(L_s/L_T)^2 >> 1$, by incorporation of density fluctuations into the model, is also considered. Radiative effects are found to increase the fluctuation level only weakly. This follows from the intrinsic coupling of the temperature fluctuations to the magnetic turbulence through the thermal force and the time dependent thermal force. Since this coupling mediates the localization, radiation only affects turbulence levels through the radial fluctuation scale. Implications for magnetic turbulence in RFP plasmas and tokamaks, including diverted discharges, are discussed.

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Simulation of Plasma Flow in a Non-Uniform Magnetic Field*

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The flow of a collisionless plasma in a nonuniform magnetic field is numerically simulated. The equations solved are those of Vlasov and quasi-neutrality. An iterative scheme for these two equations has been developed in which a Monte Carlo description for the ion dynamics is used. Ions are launched from distributed sources with finite temperature while electrons are assumed to obey the Boltzmann relation. The potential profile and the particle and energy fluxes to the wall are obtained. The results show that the electrostatic potential in the plasma depends on the profile of magnetic field strength; the pre-sheath drop increases as the magnetic field strength decreases in the direction of the plasma flow. Comparision with the analytical treatment of Sato *et al.*, [1] will be made.

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SHERWOOD THEORY MEETING 1989

Collisionless Magnetic Reconnection*

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We approach the problem of driven, collisionless reconnection by deriving a collisionless Ohm's law for the reconnection current-voltage relationship. The quantitative approach is to use test particle simulations in given reconnecting electromagnetic fields to determine the collisionless conductivity and use a resistive MHD code with the effective conductivity to determine the global magnetic fields.

For a reversed field with a constant normal component, $\vec{B} = B_{0x}(z)\hat{x} + B_{0z}\hat{z}$, perturbed by a vector potential $A_y = A_K(z)\exp(ikx + \gamma t)$, analytical estimates obtain an ion conductivity $\sigma \sim e^2 n/m_i\Omega_n$ in the regime $\gamma t_b \gg 1$, $\Omega_0\sqrt{\rho_0/a} > \Omega_n > kv_{th}$ where Ω_n and Ω_0 are the gyrofrequencies in the normal and asymptotic fields, respectively, t_b is the ion bounce frequency, a is the current sheet thickness, and v_{th} is the ion thermal velocity. This agrees with the $1/B_n$ scaling for the in-phase current response to the induction field observed in the particle simulations. Using this conductivity yields a growth rate $\gamma = \frac{4}{3}\pi^{-1/2}\frac{\rho_0}{a}\left(1 + \frac{T_e}{T_i}\right)\Omega_n\left(1 - k^2a^2\right) \leq \frac{4}{3}\pi^{-1/2}\left(\rho_0/a\right)^{3/2}\left(1 + \frac{T_e}{T_i}\right)\Omega_0$ compared with $\gamma = \pi^{-1/2}\left(\rho_0/a\right)^{5/2}\left(1 + \frac{T_e}{T_i}\right)\Omega_0\left(1 - k^2a^2\right)$ for the Landau resonance tearing mode $(kv_{th} > \Omega_n)$ (Galeev, 1982).[1]

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Second Stability Region Studies for PBXM and TFTR*

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Second region stability studies for PBXM are reported. In addition, the prospects for a second region stability experiment in TFTR is also investigated. Issues examined include the role of q_0 (and the current profile in general) in second region access, and low-n ballooning mode stability ("infernal modes"). In both PBXM and TFTR it is found that the minimum q_0 required to have total access to the second region decreases as current increases. Shaping plays an important role in determining the minimum q_0 required for total access. The more D-shaping or indentation the lower the q_0 requirements. PBXM is the logical experiment for examining this issue. Transport simulations with pellet injection demonstrate one method of raising q_0 on axis; however, the resulting q profile can be flat or inverted. This causes concern for low-n ballooning modes. A new code has been developed to look at this problem and results will be presented.

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THE RELATIONSHIP BETWEEN LOCAL TRANSPORT AND GLOBAL CONFINEMENT*

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The question of the validity of the relationship, $\tau_E \propto a^2/\chi$, arises because of several complicating factors: radiation losses, convection losses, differences between electron and ion transport, the radial dependence of the transport coefficients, and changes in the shape of the heating profile as macroscopic plasma parameters are changed. We examine this relationship between local and global confinement scaling using an approach that takes advantage of the detailed physics of the WHIST transport code. The transport code is run for the parameter regime of interest for a given experiment from which a global scaling has been deduced. The data from several runs are loaded into a LOCUS database[1] and processed, as experimental data is often processed, to deduce global scaling. This scaling is then compared with the experimental scaling to identify broad areas of agreement or disagreement. We present Ohmic and neutral beam heating examples that illustrate the influence of the non-diffusive thermal losses on global confinement. The method provides a very efficient preliminary test of new transport models, reducing manual labor and providing broad perspective on the new models' regimes of applicability.

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A GENERAL ASYMPTOTIC SOLUTION FOR LARGE ASPECT RATIO HIGH BETA EQUILIBRIUM*

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We have developed an asymptotic solution for high beta large aspect ratio tokamaks. The solution is valid in the limit $\varepsilon\beta_p = \varepsilon\langle p\rangle/\langle B_p^2\rangle >> 1$. The result is given for general $p = p(\psi)$ and $q = q(\psi)$ profiles. In this limit the solution splits into two regions, a 'core region' where ψ is a function of the major radius alone and a boundary layer of width $(\varepsilon\beta_p)^{-1/2}$. This structure gives the magnetic surfaces a marked 'D' shape. The quantity $\varepsilon\beta_I = \varepsilon\langle p\rangle a^2/I^2$ is found to 'saturate' as β is raised contrary to the claim of Clarke and Sigmar.[1] When β exceeds a critical value (the actual value depends on the profiles) a 'hole' develops at the magnetic axis. This 'hole' is a region where $\nabla p = |\underset{\sim}{B}| = 0$. These equilibrium solutions are appropriate for the study of second stability.

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THE 1989 INTERNATIONAL SHERWOOD THEORY MEETING

RAY TRACING OF MODE-CONVERTED 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. In our previous work [1], we have presented an analytical and numerical treatment of the propagation of the IBW using ray trajectory equations in toroidal geometry. The analyses showed that there can be a significant enhancement in the poloidal mode numbers of the IBW as it propagates toroidally in the plasma. This leads to an upshift in the $k_{\|}$ (the component of the wave-vector along the total magnetic field) making it possible for the IBW to Landau damp onto the electrons. Since in [1] only the wave-numbers were calculated along the ray trajectories it was difficult to determine the decay in the amplitude of the wave during propagation. Towards this end we have incorporated the amplitude transport equation [2] into the ray trajectory analysis. The numerical code follows the wave-number and amplitude evolution of IBW in toroidal geometry for a hot Maxwellian plasma. The gradients in temperature, density, toroidal and poloidal magnetic fields are included in the WKB sense in the plasma description. Results from the analyses of IBW propagation will be presented.

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The Effect of Poloidal Field on Ion-Ion Hybrid Resonance in Large Tokamaks*

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ABSTRACT

We have previously demonstrated that the propagation characteristics of waves incident upon an ion cyclotron resonance layer in large tokamaks may be significantly altered by a small poloidal field. We assume that the geometrical optics approximation is valid outside some singular layers where the resonance takes place. We treat the singular region by a boundary layer analysis, and we derive field equations valid in this region by solving the Vlasov equation. We introduce a parameter a, which is proportional to the component of the poloidal field in the direction of $\nabla|\mathbf{B}|$, and we find that when a is not zero the perpendicular stratification approximation fails. In this case, the field equation is no longer an ordinary differential equation (the local theory) and it becomes an integro-differential equation (the nonlocal theory). The solutions of this new equation also match the geometrical optics modes outside the resonance layer, and thereby enable us to construct the full wave solutions for the problem under consideration.

We first consider the case in which there is only one ion species in resonance in the layer. In the case of the minority ion fundamental cyclotron resonance we find that the reflection of the waves incident from the low field side can be significantly reduced by the poloidal effects, resulting in an increase in the wave energy absorption. Consistent with the results of the local theory, the transmission coefficient remains the same as that predicted by the geometrical optics, and there are no reflected waves when waves are incident from the high field side. In the case of second harmonic resonance, we find major differences between the results of local and nonlocal theories. There is a reduction in the transmission and the mode conversion coefficients, but an increase in the reflection of the low field side incident fast mode. We find that the wave energy absorption is dramatically increased, particularly when the parallel refractive index is small. The case of the ion-ion hybrid resonance mathematically can be represented as a combination of these two previous cases. It is not easy to predict the propagation properties on the basis of the previous results, except for the absence of reflection of the high field side incident fast mode. Thus we must rely on a lengthy expensive numerical study. We present the preliminary results of this study.

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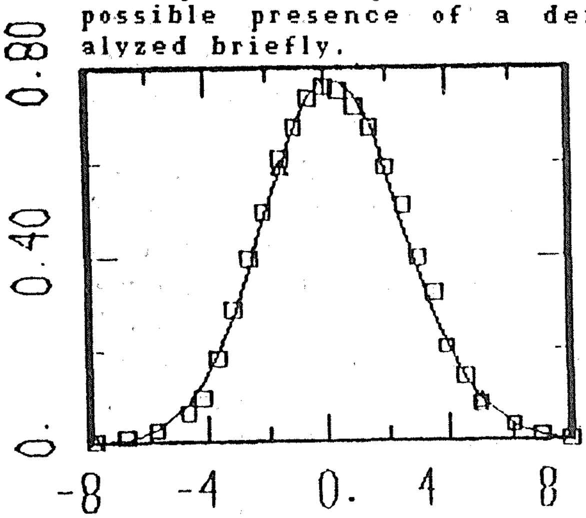
Comparison of Equilibrium Plasma Profiles with Theory Based on the Gauss-Hertz Principle.--RICHARD L. MOORE, *Moore Applied Physics Co.*--P.O. Box 6093, Tehachapi, CA 93561.

The Gauss-Hertz principle (Ref. 1) plus the constraint that the internal pressure is greater than zero leads to the prediction that the radial density profile in a plasma at dynamic equilibrium and uniform temperature is gaussian (Ref. 2). We have tested this theory using data from Racetrack experiments (Ref. 3) and from a Soviet compilation of Tokomak pressure profiles (Ref. 4). The high-resolution measurements by Kuthi (Ref. 3) show excellent agreement between theory and experiment with very small errors of estimates on the parameters of the gaussian. (See figure). The Tokomak profiles gave good fits, with larger errors of estimates, as would be expected from the greater spacing between data points. A poorer fit on one of them indicates the possible presence of a density wave and will be analyzed briefly.



Normalized pressure as a function of radius (cm), for Racetrack experiments.

We conclude that the experimental data is in good agreement with the theory.

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Two Timescale Analysis of a Coherent Current Filament in the Presence of Magnetic Microturbulence*

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In simulations of decaying two dimensional magnetic turbulence in a plasma[1], it has been observed that long lived current filaments can emerge from random initial conditions as the turbulence decays. Such structures are interesting not only because they represent a modification of the usual picture of turbulence as a collection of randomly phased normal modes, but also because they potentially affect the transport driven by turbulent magnetic fluctuations.[2]

Here, we examine this situation with an analytic theory of a single current filament in a background of magnetic turbulence fluctuations characteristic of the microtearing mode. This technique has been previously applied to fluid turbulence by examining a coherent vortex in a background of two dimensional Navier-Stokes turbulence.[3] The nonlinearities of the turbulent background, evolving on the faster time scale, are treated with standard renormalization techniques. Knowledge of the renormalized turbulent diffusivities enables a solution both for the inhomogeneous structure of the turbulence within the current filament, and for the decay time of the filament (both of which evolve on the slower time scale). This two timescale analysis reveals the minimum amplitude required for the current filamant to be long lived, as well as providing insight into the intermittency of the system, and the effects of coherent structures on magnetic transport.

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ERROR FIELD BEHAVIOR AND THE PARALLEL CURRENT PROFILE IN AN RFP*

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3-D MHD simulations of an RFP plasma exposed to static edge field errors have shown a link[1] between the parallel current profile and the behavior of the radial magnetic fields excited in the plasma volume by the edge fields. This link will be explored in two cases: (1) a model case in which the resistive evolution of the RFP equilibrium has been shut-off artificially (no "dynamo") and (2) a case in which the equilibrium evolves and resistive instabilities develop ("dynamo").

(1) No "dynamo" case: Linear MHD was used to calculate the radial magnetic field profile associated with a given edge field error. The RFP equilibrium chosen was characterized by a certain parallel current, or λ, profile: ($\lambda=\underline{J}_0\cdot\underline{B}_0/\underline{B}_0^2$). A region of finite grad-λ was seen to significantly amplify the radial field in that region (m=1 modes), unless a resonant surface ($\underline{k}\cdot\underline{B}_0=0$) was present (m=0 modes). These cases will be compared.

(2) "Dynamo" case: It has previously been observed that the introduction of edge field errors has enhanced the growth of plasma instabilities with the same mode numbers - (1,n) - as the errors. At the same time, the growth of modes with other n's has been suppressed. This suggests a change in the local parallel current profile. The extent to which this connection persists as the initial level of background plasma instability is increased with respect to the level of edge field error will be checked.

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1989 SHERWOOD THEORY CONFERENCE
SAN ANTONIO, TEXAS

A THEORY OF COLLISIONLESS TRAPPED ELECTRON MODE TURBULENCE

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Collisionless trapped electron drift waves (CTEDW) can be expected in current and future (i.e., CIT) low electron collisionality experiments. Indeed, the CTEDW can be expected to persist and be further excited by density profile peaking which quenches ion temperature gradient driven turbulence. CTEDW presents a significant theoretical challenge since the trapped electron response is hydrodynamic, with instability driven by magnetic precession resonance of higher energy particles on the tail of the distribution function. Thus, in contrast to the dissipative trapped electron drift wave, electron and ion nonlinearity must be treated on an equal footing.[1]

Here, we discuss a simple model of the CTEDW turbulence where electron dynamics are described by a nonlinear, "bounce-averaged" drift kinetic equation and where the mode structure is slab-like in character. This structure is likely to persist in the presence of turbulence. Noting that both electron and ion responses are primarily hydrodynamic, electron and ion Compton scattering, due to beat wave precession and ion Landau resonance, respectively are the dominant nonlinear processes. In particular, dispersion weakens the effect of mode coupling at short wavelengths. A wave kinetic equation has been derived. Its solution will be used to calculate the density and temperature fluctuation spectra, χ_e, D, and χ_i. The relationship to other nonlinear processes will be discussed.

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A Free Boundary algorithm for the BETAS code*

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The three dimensional spectral code BETAS [1] is extended to free boundary calculations. The formulation is the same as that of the finite difference code BETA [2], where the free boundary condition follows from minimization of the hamiltonian and can therefore be used in free boundary stability calculations. The boundary condition for the vacuum potential approximates a given winding law. Earlier spectral versions have been developped using a Green's function technique [3].

A fast iterative method for the vacuum field computation uses the spectral representation to compute an approximate inverse which serves as a pre-conditioner in the conjugate gradient method. A steepest descent iteration with damping of the high frequency modes is chosen for the first order PDE which determines the free boundary position. A small amount of artificial viscosity may be required for good convergence of the free boundary equation.

In axially symmetric Tokamak cases, the boundary values of the vacuum potential must be adjusted with the position of the plasma in order to stabilize the axially symmetric shift. Applications to l=2 and Heliac stellarators will be presented.

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Global Energy Confinement Degradation Due to Mirnov Oscillations and Other Macroscopic Phenomena in Tokamaks*

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Global energy confinement degradation caused by macroscopic phenomena in tokamaks (sawteeth, Mirnov oscillations, ELMs, etc.) has been studied using a local transport theory[1] which assumes that the heat transport is diffusive and that the macroscopic phenomena influence the plasma only in the region where they occur.

In this work we stress the Mirnov oscillation case, i.e. the effect of a saturated tearing mode on the global energy confinement. A helical flux coordinate system is chosen to solve the heat balance equation in the presence of a magnetic island. A slab model is used for the island structure and a large aspect ratio is assumed. A boundary condition for the temperature gradient ($dT/d\psi_*$) across the island is obtained from a "radial" heat flux balance across the magnetic island. To the first order in the ratio of magnetic island width to the plasma minor radius (w/a), the global energy incremental confinement time can be written as

$$\tau_{inc} = \tau_{inc0}\left\{1 - \frac{3\,\Delta T(0)}{W_0}\int_0^{\rho_s} n(\rho_0)V'(\rho_0)\,d\rho_0\right\} + O\!\left(\frac{w^2}{a^2}\right)$$

where the subscript $_0$ denotes the case without the island, ρ_s is the radius of the mode rational surface, and $\Delta T(0) \equiv T_0(0)-T(0)$ is proportional to the island width. Comparison with the "belt model",[2] which ignores the details of the magnetic island structure, shows that the present island model gives a larger energy degradation than the belt model and is in closer accord with experimental results.[3]

General τ_{inc} scaling expressions which include all macroscopic phenomena and even time dependent effects have also obtained and will be presented.

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A Self-consistent Wave-Kinetic Formulation of Wave-Plasma Interactions

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It is well known [1,2] that the ray equations of geometric optics are Hamiltonian in form with the dispersion relation, $\omega = \Omega(\mathbf{x},t,\mathbf{k})$, playing the role of the Hamiltonian and $(\mathbf{x},\mathbf{k})$ the roles of conjugate position and momentum variables:

$$\frac{d\mathbf{x}}{dt} = \frac{\partial\Omega}{\partial\mathbf{k}} \qquad \frac{d\mathbf{k}}{dt} = -\frac{\partial\Omega}{\partial\mathbf{x}} \qquad \frac{d\Omega}{dt} = \frac{\partial\Omega}{\partial t} .$$

(Here d/dt signifies the total derivative following the ray trajectory.) A wave packet moves like a classical particle in an external potential given by Ω. Because of this special property it is possible to formulate the wave propagation problem (in cases where the assumptions of geometric optics are valid) as a kinetic theory for a gas of quasiparticles [3].

By deriving the relevant equations of motion from an action principle it is possible to self-consistently couple waves to the plasma. This leads to a straightforward derivation of ponderomotive effects from a knowlege of the linear response characteristics of the medium [4].

Here we present an action principle which emphasizes the particle-like nature of ray propagation. This leads directly to a kinetic equation for the waves and a modified fluid equation for the plasma [5]. As a concrete example we then study the ponderomotive filamentation instability of an intense laser beam in a plasma.

Further generalizations and a discussion of numerical applications will also be presented.

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Three Dimensional Gyrokinetic Plasma Simulation Models for the Study of Low Frequency Microinstabilites

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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 the magnetic perturbations arising from parallel currents. Two schemes have been implemented to solve for the induced fields. The first involves solving directly for $E^T_{parallel}$, using the equation of motion, as is done in conventional Darwin magnetostatic particle sumulations. The second uses Ampere's law directly with the canonical momentum in the direction parallel to the magnetic field[1]. Both schemes give rise to shear Alfven waves as the highest frequency normal modes of the system. The equilibrium fluctuation spectra and numerical properties have been analyzed in detail in order to delineate the restrictions of the model and to verify the regime of validity consistent with the initial ordering. In addition to the ExB drifts, the curvature and grad-B drifts of the particles has been included 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 and results of drift wave simulations with trapped electrons will be presented.

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Strong Electron Heating and Stimulated Brillouin Backscatter in FEL-Heated Magnetized Plasma*

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An intense, pulsed free-electron laser is to be used to do electron cyclotron heating in the MTX experiment at Livermore. Free-electron lasers could be attractive for future use in other toroidal devices to do electron-cyclotron heating and current drive. Because of the intensity and coherence of free-electron lasers, the use of FEL's may induce parametric instabilities that may be deleterious to heating the plasma or driving current. In fact, analysis[1] has shown that there are a number of parametric instabilities to fear, the most important of which is likely to be stimulated Brillouin backscattering by electrostatic ion cyclotron waves. When the intense electromagnetic waves reach the cyclotron resonance layer, they locally heat the electrons and can significantly alter the velocity distribution. The heated distribution function can acquire a significant anisotropy and exhibit an inversion with respect to energy. Hence, the heated electron distribution may be micro-unstable; and the ensuing wave turbulence may adversely affect electron energy and particle confinement.

This paper examines some aspects of stimulated Brillouin backscatter and strong electron heating in an FEL-heated plasma. A calculation of the nonlinear saturation of Brillouin backscattering due to ion trapping and the implied back-reflection at saturation is presented. To gain confidence in this calculation, a simpler one-dimensional example of Brillouin backscatter is analyzed in which the plasma wave is a lower hybrid wave propagating perpendicular to the equilibrium magnetic field. Electromagnetic particle simulations with the ZOHAR code support the analytical calculations for the simpler model problem. Our preliminary calculations for Brillouin scattering by electrostatic ion cyclotron indicate parameter values relevant to the MTX experiment for which there could be measurable back-reflection ($> 10\%$). Using ZOHAR to do two-dimensional simulations of intense heating, we have also examined some aspects of the microstability of strongly heated electron distribution functions. The ZOHAR simulations agree fairly well with non-self-consistent orbit-code calculations of the heating and do not exhibit significant levels of micro-turbulence for the range of parameters investigated.

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Dynamics of Fluid-Polymer Solutions: An Analogue of Magnetohydrodynamic Turbulence

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It has long been known that addition of small amounts (i.e. 10 parts-per-million) of long chain polymers to turbulent fluid flow results in significant reduction in drag. Drag reduction is a consequence of the quenching of turbulence and the reduction in turbulent radial transport of fluid momentum.

While extensive phenomenological(1) and experimental studies of polymer drag reduction exist, there is no existing theoretical model of the dynamics of turbulent fluid-polymer solutions. Here we propose a simple, prototypical model. A Fokker-Planck equation for the polymer distribution function (here a function of polymer internal degrees of freedom) is derived and used to construct Eulerian moment equations for polymer concentration density and chain length. Similar arguments are used to construct the stress tensor which determines the back-reaction force of the polymer on the fluid. The coupled equations for the fluid and polymer chain length closely resemble the familiar MHD equations, with the chain length field playing a role analogous to the magnetic field in MHD. Thus, exchange between fluid kinetic energy and polymer elastic energy follows naturally. We show that in this 'polymer hydrodynamic' system, the fundamental excitation is an 'elastic' eddy analogous to the "Alfvenic' eddy of MHD.(2) As polymer chains support a spectrum of relaxation modes(3) dissipation associated with the Stokes drag on internal stretching motion leads to enhanced internal energy damping in the theory. This enhanced damping leads to a lossy or truncated energy cascade, which corresponds to quenching of turbulence and drag reduction.

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Temperature Gradient Driven Instabilities in FRCS*

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Experimental and theoretical studies have clearly shown that transport in FRCs is not classical and a number of instabilities, including the lower hybrid drift instability and low frequency drift waves, have been proposed to explain these anomalous features. While transport models based on low frequency drift wave turbulence seem to yield results in reasonable agreement with the experiments there are other modes that could contribute to the transport.

It has been shown lately that temperature gradient driven modes play a very important role in tokamak transport and therefore it is of interest to study these modes within the FRC context. Considering perturbations in the electrostatic potential and all three components of the vector potential and using fully magnetized models for electrons and ions we derive a local dispersion relation that includes all relevant finite β effects. Solving this dispersion relation numerically we show that the temperature gradient can drive unstable modes over a wide range of values of β and η ($\eta = nT'/n'T$) and present the dependence of mode frequency and growth rate on relevant plasma parameters.

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STABILITY WINDOW FOR INTERNAL GLOBAL MODES IN IGNITING PLASMAS⋆

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The "window" (in parameter space) within which a plasma column is stable against internal global modes with $m^0 = 1$ is discussed. This stability window arises when a high energy particle population is present in the plasma. Energetic ions can stabilize "sawtooth" oscillations[1,2] and destabilize "fishbone" oscillations[3,4]. However, a stable gap in the poloidal beta β_{ph} of the energetic ions (stability window) between the onset of low-frequency[3] $\omega \sim \omega_{*i}$ and high frequency[4] $\omega \sim \overline{\omega}_{Dh}$ fishbone oscillations appears when $\omega_{*i} << \overline{\omega}_{Dh}$ - ω_{*i} being the bulk ion diamagnetic frequency and $\overline{\omega}_{Dh}$ a characteristic value of the magnetic precession frequency of the energetic ions -. We observe that the onset of the low frequency fishbone occurs at a point where the effective mode free energy is low enough that the ideal internal kink (responsible for the sawtooth crash) is stabilized.

The dependence of the width of the stability window upon several plasma parameters is examined in the case of an igniting plasma with high energy, fusion produced α-particles. In particular, it is found that there is a strong dependence on the location r_s of the $q = 1$ surface, the stability window being dramatically reduced for $r_s/a > 1/2$. Decreasing the value of q on axis, while keeping the location of the q=1 surface unchanged, effectively delays the stabilization of sawteeth to higher values of the α-particle density.

A spin polarization of the D-T fuel can produce a population of anisotropic α-particles, but it is shown to have a minimal effect on the stability window.

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3-D Modeling, Simulation and Evaluation of ICRF Antennas

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ICRF heating has been applied to present day tokamak devices with varying degrees of success; heating is observed but sometimes with adverse effects of unknown origin which may be due to plasma and/or antenna-specific causes (to date these adverse effects remain unknown). Future plans for devices such as CIT and ITER call for ICRF auxilliary heating but at power levels considerably higher than presently used. Successful ICRF heating of these future devices will depend critically on the ability to design and construct antennas which are optimized for a specific plasma configuration. Because of the much higher power levels there is a clear need to design and predict antenna performance with a high degree of confidence. Such a capability has recently been developed; it is now possible to carry out a 3-D simulation of fairly arbitrary realistic ICRF antenna configurations including multiple current straps, power leads, variable Faraday shield geometry and other geometrical details. The antenna simulation is based on the SAIC ARGUS 3-D plasma simulation code which has been used in a wide range of electromagnetic device problems[1,2] with considerable success. We will describe details of the simulation method and code, as well as the results of a detailed simulation of the ICRF antenna currently under development by the University of Wisconsin and planned for use in the Wisconsin tokamak. The simulated antenna includes current straps, Faraday shield, sideshields and end caps. The simulation focuses on the vacuum near field pattern and the self-consistent current distribution on the strap. The results are in excellent agreement with the Wisconsin experimental data.[3] We will show how conventional 2-D[4] code results can be "adjusted" to agree with the 3-D code and experimental data. Our work demonstrates the potential to be realized from an increased effort in the further development of full 3-D antenna-plasma coupling simulation and the impact on the design, analysis and evaluation of real ICRF antenna configurations.

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DISSIPATIVE TRAPPED ELECTRON MODES IN $\ell = 2$ TORSATRONS*

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In contrast to tokamaks, stellarators have the advantage that the vacuum magnetic field can be changed substantially by modifying the currents in the vertical field coils [J. F. Lyon, B. A. Carreras, et al., Fusion Tech. **10**, 179 (1986)]. In ATF, for example, changing the dipolar or quadrupolar moment of the VF coils changes $|\mathbf{B}|$ along the field line, therefore changing the trapping regions and local curvature. It is of interest that this presents the opportunity of changing the ratio of the helically to the toroidally trapped particles. We are looking at ways to design experiments in ATF to study dissipative trapped electron modes [B. B. Kadomtsev and O. P. Pogutse, Sov. Phys. Dokl. **14**, 420 (1979)], and their role in plasma confinement. We are working on a tractable but realistic model for studying such modes in $\ell = 2$ torsatrons. Results will be presented for an ATF configuration.

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Finite Mean Free Path Corrections to Parallel Heat Flow in Divertors *

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The heat flux along magnetic fields lines in tokamak divertors is carried mainly by electrons. Because the heat flux is dominated by high-energy electrons, important departures from Spitzer conductivity can occur when the collisional mean free path for thermal electrons, λ, is still small compared to the temperature scale length, L_T. This problem has been considered previously for an ad-hoc model temperature profile[1] and for laser-fusion plasmas.[2] Here we study this problem for temperature profiles obtained from a diffusion equation with reduced Spitzer conductivity using the Monte Carlo code MCPAT which solves the Fokker-Planck equation along the magnetic field. It has been customary to characterize the heat flux as limited to a fraction of the thermal flux, nTv_t.[3] In limit that $\lambda/L_T \approx 1$, we find a heat flux given by $\approx 0.15nTv_t$, where $v_t^2 \equiv 2T/m$. Note that sometimes the definition $v_t^2 \equiv T/m$ is used, in which case the numerical coefficient increases from 0.15 to 0.21.

In addition to the conductivity being reduced, the energy spectrum of the electrons being lost over the sheath potential at the divertor plate can exceed the fluid value of $2T$ by a factor of 3 or more for $\lambda/L_T \geq 0.2$. An analytic model of the distribution function gives a reasonable fit to these MCPAT results. The increase in the energy lost per electron results in a decrease in the temperature at the plate, and the associated decrease in the sheath potential should reduce physical sputtering. Implications for DIII-D and ITER will be discussed.

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Particle Simulations of Finite Beta Resistive g-Mode in Sheared Slab Geometry*

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Particle simulations of finite beta ideal and resistive g-modes in sheared slab geometry are carried out by using a 'reduced' $2\frac{1}{2}\,D$ magnetoinductive code which includes the shear-Alfvén branch only. Parallel electron dynamics are followed exactly while their perpendicular velocities are given by $\mathbf{E} \times \mathbf{B}$ and $\mathbf{g} \times \mathbf{B}$ drifts. Full ion dynamics are treated. An accurate Lorentz collision operator is used for the simulation of resistive plasmas. Eigenmode structures, growth rates and mode widths are compared with the linear theory results that are obtained by a 4th order shooting code and show good agreement. Finite beta stabilization is achieved at beta values on the order of the square root of the mass ratio for the ideal interchange mode. Stabilization begins when beta is on the order of the mass ratio. When L_n/L_c is zero, drift modes and shear Alfvén modes are recovered. With the inclusion of resistivity, destabilization in the linear phase is also obtained and is in agreement with the linear theory results. Nonlinear analyses such as the calculation and measurements of magnetic fluctuation levels in both theory and simulations are in progress.

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A Knowledge Engineering Based Expert System Interface for an NMFECC Plasma Physics Tool Box Utility*

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We are investigating the construction of an NMFECC Plasma Physics Tool Box utility which would consist of a collection of plasma physics applications packages organized under the BASIS structural format and accessible through an expert system interface on the MFE network. The interface would use a combination of natural language processing and menu driven directives to construct I/O environments appropriate to a chosen application, both with respect to the description of relevant physical parameters as well as the processing of results of the computation.

The intent is to automate and enhance user accessibility to self-contained, mature physics applications within the MFE network environment.

The interface would support user directed inquiry based on knowledge structures with regard to the contents and limitations of package models, I/O, supporting publications, and utilization history.

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Coupled Energy and Particle Transport Near a Separatrix

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The coupled electron and ion energy equations and the particle conservation equation are solved numerically using finite difference methods in a boundary layer enclosing the separatrix of a diverted tokamak. Ion inertia and viscosity are neglected, so that the total pressure is constant on a magnetic surface, and is determined by the surface-averaged particle conservation equation. The parallel current density and the electrostatic potential are determined by charge conservation and Ohm's law. Outside the separatrix, the boundary conditions at the divertor plates completely determine the potential and the electric field, while inside the separatrix, the momentum input and momentum transport (viscosity) are needed to completely determine the radial electric field. The neoclassical contributions to confinement of particles, momentum, and energy are then determined.

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EFFECTS OF NEUTRAL INJECTION AND NEUTRAL RECYCLING ON TOKAMAK CONFINEMENT*

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Effects of powerful neutral injection and neutral gas recycling on tokamak confinement have been studied by means of particle simulations in a toroidal system. The code follows either guiding center particle orbits for both ions and electrons or guiding center electrons and full dynamic ions. For a perpendicular or near perpendicular injections, it was found that the electrostatic potential develops an asymmetric profile in the poloidal plane due to the trapped beam ions. Such an asymmetric potential can enhance the neoclassical ion transport by a factor of few if the amplitude of the asymmetry is (5 ~ 10)% of the thermal plasma temperature. The effect of the cold neutral gas recycling on plasma confinement is studied by recycling cold neutral gas at the edge of a tokamak plasma. Preliminary results indicate that the edge potential may be determined by the cold neutral temperature thereby reducing the edge potential fluctuations which may help improve edge confinement. Details will be discussed.

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Magnetohydrodynamics and Nonlocal Resistivity Combined in Reversed Field Pinch Profile Sustainment*

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It has long been recognized that symmetry breaking magnetic field fluctuations are required to sustain toroidal field reversal in the steady state Reversed Field Pinch (Cowling's Theorem). In the MHD model,[1] the average poloidal current, $\langle J_\theta \rangle$, is driven outside the field reversal radius by a cross product of plasma velocity and field fluctuations, $\langle \delta \mathbf{u} \times \delta \mathbf{B} \rangle_\theta$. In the kinetic dynamo theory (KDT), a nonlocal Ohm's law is postulated to drive $\langle J_\theta \rangle$ near the plasma edge. Long mean-free-path electrons are accelerated by the toroidal electric field in the plasma core. These electrons carry momentum along stochastic magnetic field lines to the edge reversal layer where they sustain poloidal current in the absence of a poloidal electric field.

In this paper, the Boltzmann equation is used to study electron current both parallel and perpendicular to $\mathbf{B}$, while quasineutrality is maintained. The current distribution parallel to $\mathbf{B}$ is dominated by fast electrons, while cross field currents are driven by a slower electron component. The ratio of current fluctuations to electric field fluctuations parallel to $\mathbf{B}$ can be significantly smaller than the average resistivity would indicate. This is particularly true when the electron mean-free-path is long compared to the scale of variation in $E_{||}$ and $J_{||}$. This example of nonlocal resistivity is quantified, and the linkage of MHD and the KDT in Reversed Field Pinch sustainment is estimated.

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NONLINEAR CORE PLASMA RESPONSE TO RF POWER ABSORPTION AND TRANSPORT IN TOKAMAKS*

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The steady state Fokker-Planck code, RFTRANS, with two velocity space dimensions and one real space dimension (to include transport effects) has been coupled to the one dimensional full-wave code, ORION-S. The nonlinear response of a minority species and the resulting effect on the propagation and absorption of both fast waves and Ion Berstein waves for a simple tokamak model has been calculated. Results showing the response for various power levels while using a simple diffusive "turbulent-like" kinetic transport model will be presented. A simple rf quasilinear operator that is "homogenized" over a flux surface is used to estimate the velocity space response in the presence of Coulomb collisions with other fixed plasma species and an energy conserving model is used for Coulomb self collisions.

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

Unified Theory of Ballooning Instabilities and Temperature Gradient Driven Trapped Ion Modes

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A unified theory of temperature gradient driven trapped ion modes and ballooning instabilities is developed by constructing a variational form of kinetic theory in banana collisionality regimes. All known results, such as electrostatic and purely magnetic trapped particle modes and ideal MHD ballooning modes are readily derived from our single general dispersion relation. We find that long wavelength toroidal instabilities are likely to be present over a wide range of α ($\alpha = -q^2 R_0 d\beta/dr$ is a measure of the local shafranov shift), with the electrostatic branch dominant at low α, the shear Alfven branch dominant at moderate α, and compressional Alfven branch dominant at high α. A model Lorentz operator is used to introduce collisional dissipation into the unified theory which produced dissipative trapped particle modes, dissipative drift ballooning modes and stabilized purely magnetic trapped modes. Those residual dissipative instabilities appear to persist up to larger α values associated with the "second stability" ballooning regime.

SHERWOOD THEORY MEETING 1989

A New Method to Measure q-Profiles Using a Diagnostic Neutral Beam*

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We propose a new method to make direct, time resolved, local measurements of the full pitch angle profile of the magnetic field using a well collimated diagnostic neutral beam. The method relies on observation of neutral particles coming from charge exchange of injected fast ions. Unlike other measurements, we inject the fast ions with very small parallel velocity. The signal at the beam energy is predicted to be highly peaked in the plane perpendicular to B. This is due to the small momentum transfer involved in charge exchange reactions. Results of a pilot experiment done with the existing TEXT neutral beam and a single detector agree well with our predictions, although the current location of the detector does not allow q measurement. Plans to install a new detector array capable of a full vertical scan are underway. It will have enough angular and time resolution to see sawtooth activity near the plasma center.

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

Transport Modeling of PBXM

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Transport and stability calculations of the PBXM tokamak are presented. MHD studies indicate that broad current density profiles with elevated values of q_0 are required to access the second stability region. Using a time dependent, flux surface averaged transport code we explore some possible scenarios for establishing and maintaining such profiles using pellet injection and neutral beam heating.

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Test for Rippling Mode Transport at the Edge of TFTR

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Anomalous transport due to rippling modes, as summarized in the Ross report[1], is calculated to be proportional to the toroidal electric field, E_o, raised to the 4/3 power. The precise values of χ_e and D which might be derived from nonlinearly saturated rippling mode turbulence could be open to question. However in an experiment the absence of a driving term in the form of E_o or, equivalently, j_{tor}, should unambiguously reduce the anomalous transport due to rippling modes to a negligible value. During the current ramp-down phase in TFTR (and many other tokamaks) the toroidal electric field passes through zero in a region near the edge of the plasma. We have used the time-dependent TRANSP transport analysis code to calculate $E_o(r,t)$ and $\chi_e(r,t)$ on the basis of measured $T_e(r,t)$, $n_e(r,t)$, $P_{rad}(r,t)$, and $Z_{eff}(t)$ during the current ramp-down phase of a number of ohmically heated TFTR discharges, at varying densities. We see no evidence of a reduction of χ_e in the region where $E_o \approx 0$. Furthermore we see no evidence of significant changes in the turbulent $\dot{B}_\theta$ spectrum. Thus we conclude that rippling modes, or other instabilities strongly dependent on local current density, play a negligible role in transport at the edge of these TFTR plasmas.

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SHERWOOD THEORY CONFERENCE
April 3 - 5, 1989

Pulse Length and Ignition Probability Studies for the Compact Ignition Tokamak*

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The physics and engineering assessment of the Compact Ignition Tokamak (CIT) has led to the development of two zero dimensional power balance codes. The purpose of the first is to analyze pulse length and heating requirements for CIT. This time-dependent code has been benchmarked against the Tokamak Simulation Code which uses theory-based thermal diffusivities. After performing a series of runs at various levels of confinement, the time to ignition will be parameterized in terms of the auxiliary power available and the power required to reach ignition.

The second code (time-independent) provides a probabilistic assessment of CIT performance. Critical parameters for the zero dimensional calculation are assigned probability distributions based on recent experiments and on expectations for CIT. Not surprisingly, the uncertainty in the level of energy confinement is the largest contributor to the width of the resulting ignition probability distribution. The level of thermal transport at ignition will be compared to that predicted by theory-based scaling expressions.

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ON THE ROLE OF ELECTROMAGNETIC MICROTURBULENCE IN OHM'S LAW AND DISSIPATIVE FLUID INSTABILITIES

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Resistive fluid models have served plasma physics as a useful paradigm for turbulence and anomalous transport. Indeed, the utility of such models is surprising in view of the fact that present-generation confinement experiments operate at very low electron collisionalities. This observation naturally motivates one to investigate other mechanisms for decoupling field and fluid motion, such as dissipation of magnetic energy induced by turbulence.

In this paper, we consider the turbulent dissipation of magnetic energy due to electromagnetic microturbulence. An effective Ohm's law, which includes the effect of spatial scattering of electrons by turbulence, is derived from the renormalized electron drift kinetic equation. The resulting expression incorporates collisional dissipation, fluctuation-amplitude-dependent electron viscosity, and counter-terms which preserve the symmetries and conservation properties of the system. The turbulent electron viscosity dissipates magnetic energy by scattering electrons through the mode, thus diffusing the current perturbation. Using the effective Ohm's law, we then investigate the saturated state of dissipative pressure-gradient-driven turbulence. The role and relative importance of dissipation are assessed. In particular, the roles played by the turbulence in destabilization (i.e., viscous dissipation of magnetic energy) and saturation (i.e., diffusion of pressure) are treated on an equal footing. We conclude by discussing the generic properties of dissipative fluid turbulence at low electron collisionalities.

THE EFFECT OF NEUTRAL BEAM-DRIVEN CURRENTS ON THE NONLINEAR DYNAMICS OF MAGNETIC ISLANDS

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The nonlinear evolution of a single-helicity tearing mode in the presence of an injected distribution of energetic ions is analysed using the drift kinetic equation. Asymptotic analysis of the Grad-Shafarnov equation for an island is used to determine the time dependence of the magnetic island-width. Included in the model are previously found modifications to island growth due to bootstrap currents[1,2] and interchange effects.[3] For typical neutral beam parameters, the contribution to the island current due to neutral beams is comparable to that of the bootstrap current. For island sizes larger than the linear tearing layer-width, the island neutral beam current, bootstrap current and interchange effects dominate the island growth initially. For island widths larger than a critical island width, the island grows at the Rutherford rate.[4]

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ICRF Full Wave Field Solutions and Absorption for D-T and D-He Scenarios*

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We consider a fundamental power conservation relation, full wave solutions for fields and power absorption in moderate and high density tokamaks. These include D-T and D-^{3}He scenarios for TFTR, JET and CIT at the fundamental, second and third harmonics. Optimum single pass absorption cases for D-T operation in JET and CIT are considered as a function of the $k_{\|}$ spectrum of the antenna with and without a minority He^3 resonance. It is found that at elevated temperatures >4 keV, minority (10%) fundamental deuterium absorption is very efficient for either fast wave low or high field incidence or high field Bernstein wave incidence. In addition, scenarios with ICRF operation without attendant substantial tritium concentrations are found the fundamental (15%) and second harmonic helium (33%) heating in a the deuterium plasma. For high field operation at high density in CIT, we find a higher part of the $k_{\|}$ spectrum yields good single pass absorption with a 5% minority helium concentration in D-T.

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SHERWOOD THEORY MEETING 1989

Kinetic Modification of Nonlinear Toroidal η_i Mode*

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Recent kinetic study[1] shows that the toroidal η_i-mode is unstable when $\eta_i > 2/3$ and $\varepsilon_{Ti} < 0.35$ for normal and flat density profiles and when $\varepsilon_{Ti} < \Gamma_0(b)/(1 + T_i/T_e)$ for inverted density profiles. The real frequency of the toroidal η_i-mode varies as $\omega_r \cong -k\varepsilon_n(1 + \eta_i/2)$ which means the $\omega = \omega_{Di}$ resonance is essential and the growth rate is smaller than the real frequency in most cases which implies the weak turbulence study for this mode is necessary. Using the renormalized turbulence equation from the nonlinear gyrokinetic equation[2] we obtain the nonlinear damping rate and discuss the dominant nonlinear saturation mechanism. Some aspects of the nonlinear saturation mechanism considered here are investigated by Lyster and Leboeuf in this meeting. Balancing the linear growth rate with the nonlinear damping rate, we obtain the anomalous ion thermal conductivity, $\chi_i \sim 2\frac{q}{s}k_0\frac{\eta_i - \eta_c}{\tau}\frac{\rho_s}{r_n}\frac{cT_e}{eB}$ where k_0 is the wavenumber at which the linear growth rate is maximum.

Also the plasma current dependence of the χ_i is discussed, which enters into χ_i formula through q dependence of the η_i critical.

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HELICAL COIL DRIVEN SAWTEETH*

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Sawteeth are widely believed to control plasma profile shapes in tokamaks. When sawteeth are not present, plasma impurities become peaked in the center. Helical coils may be used to generate sawteeth to control profiles and impurity levels. Following [1], the reduced MHD equations with parallel and perpendicular heat conductivity are used to simulate helical coil driven sawteeth. Profile modification as a function of the period and amplitude of the driving coils is discussed.

[1] R.E. Denton, et al., Phys. Fluids 30, 1448 (1987).

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INFLUENCE OF TRAPPED-ELECTRON-PRESSURE-GRADIENT-DRIVEN TURBULENCE ON SUPERSHOT CONFINEMENT*

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Previous studies have indicated that collisionless trapped-electron instabilities are likely to be the most prominent type of microinstability active in peaked-density-profile, collisionless plasmas such as TFTR supershots. In the present work, the pressure-gradient-driven turbulence associated with these modes is analyzed with toroidal rotation (associated with unbalanced neutral beam injection scenarios) taken into account. The principal results are:

(i) The toroidicity-induced mode structure[1] is typically maintained in the presence of rotation $v_\phi(r)$. Therefore, the shear-induced damping is negligible for these fluctuations.

(ii) The fluctuations-induced ion thermal diffusivity (χ_i) and ion momentum diffusivity (χ_ϕ) are roughly the same.

(iii) The observed improvement in confinement could be due to the fact that there are fewer resonant trapped electrons when the density profile is sufficiently peaked.

Finally, the competition between the ion Compton scattering[2] (which transfers energy to longer wavelengths) and trapped-electron-induced scattering[3] (which transfers energy to shorter wavelengths) processes as the dominant nonlinear saturation mechanism is critically examined in the presence of gradients in $T_e(r)$, $T_i(r)$, and $v_\phi(r)$.

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Consequences of n=1 toroidal misalignments between coil and inner wall limiters

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Misalignments between the toroidal field coils and the inner vacuum vessel wall, which acts as a limiter for non-diverted discharges in Alcator C-mod, induce toroidal and poloidal asymmetries in the outer plasma. These are of interest because of the implications for heat flux deposition and because of effects on transport in the plasma edge. We consider a situation in which the centerlines of the toroidal field magnets and the vacuum vessel wall are offset by $\delta R_{\text{cylinder}}$. The scale length for such an offset to affect the plasma is the energy scrape off length. In Alcator C this was ≈ 4 mm. Similar phenomena are produced by a non-coincidence of poloidal limiters and the outer flux surfaces leading to scrape off on "hot spots". The effects on the outer plasma are investigated in a qualitative fashion by considering only the effects of radial diffusion on the outer field lines. Parallel dynamics are not considered and the flow velocity and diffusion coefficients are taken as constant. Heat flux patterns to the inner vacuum vessel wall and variations of plasma density within a flux surface are investigated as a function of misalignment and $q(a)$. The implications of such variations for possible transport mechanisms are considered.

[1] Work supported by the U.S. Department of Energy under Contract No. DE-AC02-78ET51013.

CONSIDERATIONS OF ELECTRON DYNAMICS IN A GYROKINETIC PLASMA*

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As a natural progression for the development of gyrokinetic particle simulation techniques,[1] we are presently investigating the issues concerning the electron dynamics in a gyrokinetic plasma. Specifically, the electrons are responsible for the transit time requirement, $k_{\parallel} v_{te} \Delta t \lesssim 1$, as well as the enhanced thermal (noise) fluctuation in the simulation. Since we are mostly interested in low frequency microinstabilities, it is desirable to modify the electron dynamics accordingly so as to mitigate some of these restrictions. This has been accomplished in the case of simulating ion temperature gradient drift instabilities[2], in which the electron response is assumed to be adiabatic, i.e., $\delta n_e / n_0 \cong e\Phi / T_e$, because of the linear property of $|\omega| << k_{\parallel} v_{te}$. Consequently, the simulation plasma is much quieter and a much longer time step is used. For simulating trapped particle instabilities, we propose a set of bounce averaged equations of motion for the banana centers for the trapped electrons, whereas the passing electrons behave adiabatically. Thus, important properties such as those associated with magnetic and E×B drifts are preserved. This type of approach is essential as the first step in toroidal simulation. However, a more general scheme, in which the all-important wave-particle interactions are kept without degrading the numerical properties of the simulation plasma, is the ultimate goal of our investigation. One possibility is to introduce magnetic perturbations into the simulation by taking advantage of the appearance of kinetic shear-Alfven oscillations,[3] which can reduce the frequencies for the normal modes and, consequently, can lower the associated noise level. The techniques to circumvent the condition of $k_{\parallel} v_{te} \Delta t \lesssim 1$ in a system with fast electrons and slow waves will be presented.

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The Bootstrap Current in Stellarators

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We have derived an expression for the bootstrap current in stellarators under the usual approximation of neoclassical theory that the fraction of trapped particles is small and that the mean free path is long. In this approximation, the bootstrap current on each magnetic surface is determined by a dimensionless number. This number is calculated by field line integrations that require only the field strength in magnetic coordinates and the rotational transform. The limited information that is required is a special case of a general result. The neoclassical transport of a plasma in a toroidal device with magnetic surfaces is determined by the variation of the field strength in the magnetic surfaces and the rotational transform alone. The shape of the magnetic surfaces is irrelevant. The relative dependence of the bootstrap current on the density and temperature gradients is found to be the same in any device with a small fraction of trapped particles as in a large aspect ratio tokamak. In asymmetric fields, the maximum value of the field strength on a surface occurs at only one point per period. We find that magnitude of the bootstrap current is sensitive to the angle with which the magnetic field lines cross that point. Numerical determinations of the bootstrap current have been made for several field configurations and the results have been compared to other techniques for evaluating the bootstrap current.

Self-Consistent Collision Code for Beam Tracking*

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The beam dynamics for an electron (or positron) storage ring and for the Superconducting Super Collider at the collision point is crucial in determining the maximum luminosity of the beam. For typical parameters of SSC the beam density is sufficiently high ($\sim 10^{15}$ cc) at the collision point and the interaction time sufficiently long ($\Gamma t_{\rm coll} \sim 0.1$, where $\Gamma = \frac{1}{2}\omega_{pi}/\sqrt{\gamma}$), so that effects of not only the rigid body beam-beam interaction but also the softer beam-beam collective interaction should be assessed. A relatively simple model has been introduced to analyze the above problem in a self-consistent manner by particle simulation method. Relativistic particles interact self-consistently with each other over the collision time $t_{\rm coll}$ and then their transverse position (or betatron coordinates x, y) and beam angles (or aperture) θ_x, θ_y are transformed in a simplectic map of the magnets that lie between the collision point to the next. This is repeated over a necessary number of time steps. A preliminary result on the filamentation mode and heating will be discussed.

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INVERSE CASCADES IN 2D COMPRESSIBLE TURBULENCE

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A fundamental property of forced, dissipative 2D incompressible Navier-Stokes [NS] systems is the dominance at long times of the longest wavelengths available to the flow. This dominance, attributed to an inverse cascade of energy with respect to enstrophy[1], has been observed in spectrally accurate numerical simulations[2, 3] of the incompressible NS equations. We extend the numerical investigation of this behavior to the compressible regime by means of our spectral methods code, *COMBOX*.

COMBOX solves the 2D NS equations for an ideal gas with constant viscosity and thermal conduction coefficients. Periodic boundary conditions are a natural result of the complex Fourier series expansion basis used in the code. In the absence of external forcing, *COMBOX* exactly conserves density, momentum and total energy. The forcing function we choose for this study is divergenceless, imparts no net momentum, and stirs the fluid in a wave number band in the neighborhood of $k_f = 8$.

We compare results from *COMBOX* simulations with an average Mach number of 0.18 with those from identically forced incompressible simulations, at Reynolds numbers of a few hundred. The wavenumber dependence in the enstrophy cascading region is very similar in both cases. Inertial range behavior differs; in the compressible case the spectrum is flatter than in the incompressible limit. A dual power law is also observed in density and pressure fluctuations, in the compressible simulations. Most significantly, continued ($k_f = 8$) forcing leads to overall continued growth in the longest accessible velocity field wavelengths, in *both* the incompressible and compressible cases.

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Analytic Model for Electron Cyclotron Heating Profiles*

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A model is described which uses ray tracing to scale electron cyclotron heating profiles, $P(\psi)$, over a range of plasma beta. The form of the equation is $P(\psi) = A(\psi)g(\omega_{pe}^2/\omega^2) \times \{1 - \exp[(-N_e T_e f(\psi)]\}$. $A(\psi)$ represents the predicted profile for the unperturbed rays in a low beta plasma, $g(\omega_{pe}^2/\omega^2)$ represents the perturbation to the ray trajectories due to finite density, and the last term gives the scaling law for an "average" ray in the given geometry. This simple model can be used to predict $P(\psi)$ for arbitrary beta without necessitating a possibly expensive ray tracing run. One obvious application is as an input to time dependent transport codes where the heating term's contribution can be updated as often as desired for essentially no computational cost. Our initial application for this model is to the lengthy and laborious calculation of treating the rays which scatter from the vacuum chamber walls of ATF. The current level of sophistication allows realistic prediction of heating profiles from low plasma beta values up to weakly relativistic and moderately dense plasmas with arbitrary profile shapes.

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LOWER HYBRID WAVE PROPAGATION AND ABSORPTION IN A TOKAMAK*

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Wave propagation and absorption in a tokamak at lower hybrid frequencies are studied computationally on the basis of exact Solviev equilibria and the cold plasma model. We have presented previously [1] results from a code based on Maxwell's equations with the cold plasma dielectric tensor in exact tokamak geometry. Results from that code were severely limited by what we conjectured was an apparent, numerical and non-physical, resonance. We present results from a second code that shows clearly that the additional resonance is non-physical and purely associated with numerical problems. While the results from this code are clear and straightforward, we find that it is computationally extremely slow and demands very large computer memory allocations. We show how to modify the faster and smaller first code so as to take into account the knowledge of the spurious resonances and to achieve a small, fast code with greatly reduced spurious resonances. We use this code to explore lower hybrid wave propagation and absorption in small tokamaks. We show clearly that the nature of the true plasma resonance described in the cited paper is correct.

[1] Applications of Radio-Frequency Power to Plasmas, Seventh Topical Conference, Kissimmee, Fl., 1987, eds. S. Bernabei and R.W. Motley, pp. 203-206.

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Singular Adiabatic Approximation to Low-Resistivity Magnetofluid Dynamics

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This continues our studies of singular solutions of adiabatic magnetofluid dynamic (MFD) equations (Grad-Shafranov) in relation to low-resistivity MFD (Grad-Hogan). For these studies we have used a 2D simulation of an oscillating doublet for which there are two magnetic islands bounded by a separatrix in the form of a figure-eight. In the adiabatic case, the separatrix is a singular surface which supports jump discontinuities in the field and fluid variables. This simulation is a generalized solution of the adiabatic equations which admits dissipation in and reconnection across the separatrix. In the low-resistivity simulation, the separatrix is not singular but is surrounded by a thin sheath or boundary layer which contains almost all the dissipative effects in the fluid. Elsewhere [1], we have discussed the thinning of the sheath in the limit as η, the resistivity, becomes small. The approximation to low-resistivity solutions by a singular adiabatic solution is understood in terms of the adiabatically invariant profile $\mu(\psi)$ which appears in the Grad-Shafranov equation

$$\Delta\psi = -\frac{d}{d\psi}\left(p + \frac{B_z^2}{2}\right) = -\mu'(\psi')^{\gamma-1} - \gamma\mu(\psi')^{\gamma-2}\psi'' - \nu\nu'(\psi') - \nu^2\psi''$$

The profile μ is defined in terms of thermodynamic variables. Here ψ is magnetic flux and V is the volume (area) of plasma contained within a flux surface (contour). The prime denotes differentiation with respect to V. We use a resistive analog μ_η to the adiabatic profile. The resistive profile μ_η has an infinite singularity at the separatrix but approaches a profile with a finite jump discontinuity as $\eta \to 0$. From calculated values of μ_η we estimate $\mu = \lim \mu_\eta$ as $\eta \to 0$ for a suitable family of resistive solutions and use this limiting μ to obtain the appropriate singular solution of the adiabatic equations. Using the set of such solutions that describe the oscillating doublet, we calculate the total reconnection adiabatically.

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Lower-Hybrid Wave Penetration with GW Pulsed Power in ITER*

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Conventional lower-hybrid heating and current drive is usually limited to the edge region of a reactor-grade plasma because of strong electron Landau damping of waves which are accessible to the core. The advent of intense, pulsed lower-hybrid sources, such as an induction-linac-driven relativistic klystron, opens the possibility of enhanced penetration by forming a nonlinear plateau. We estimate the optical thickness as a function of incident power and machine parameters in the limits where the effective pulse repetition time is long or short compared to the collision time. The results are sensitive to the plateau width, which in turn depends on the $N_{\|}$ spectrum, nonlinear orbit effects and possibly diffraction. We have incorporated the nonlinear absorption model in a ray-tracing code. Code results confirm the analytic estimates of optical depth and also indicate that, for an ITER equilibrium, an initially narrow spectrum of rays remains narrow until the rays reach their closest approach to the axis. We also compare our analytic penetration formula with results from the multi-particle orbit code ORPAT. For nominal ITER parameters, significant penetration occcurs for peak powers in the multi-GW range. We explore the susceptibility of such intense pulses to parametric instabilities, the most important of which is the decay into an ion-cyclotron quasi-mode and a lower-hybrid sideband near the plasma edge. For 20 ns pulses, 1 m wide beams and a 1 keV electron temperature, convective and temporal growth criteria are approximately the same. Results to date indicate that, to avoid excessive growth ($>$ 6 e-folds), the peak power density near the edge of an ITER-like plasma must be kept below a few GW/m^2 or the pulse must be shortened. Hence parametric instability and penetration requirements determine an operating window of acceptable peak powers. Finally, we present preliminary calculations of a charge-separation effect that produces a penetration-enhancing potential.

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TURBULENT TRANSPORT IN TOKAMAKS DUE TO DRIFT-ALFVEN FLUCTUATIONS.*

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We study the anomalous electron transport in tokamaks, using the perturbative method developed in ref(1). The electrons are described by the nonlinear drift-kinetic equation, and the transport is analysed through the renormalized response function in presence of drift-Alfvèn fluctuations.

We obtain the complete transport matrix, and examine the relations between the incremental particle fluxes, parallel and perpendicular heat fluxes, and current diffusion, due to perturbations in the density and temperature profiles of the plasma.

We combine observed fluctuation spectra with our theoretical results to predict heat pulse diffusion and particle transport in TEXT. These predictions are compared with some recent measurements.

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COMPARISON OF BALLOONING MODE STABILITY PROPERTIES OF TOKAMAKS WITH DIFFERENT CROSS SECTIONS AND THE SAME POLOIDAL FLUX*

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The desire to confine high pressure plasmas in tokamak reactors, while using only moderately high plasma currents, has led to increased interest in getting into the second stable region for ballooning modes.[1–5] Increasing the safety factor at the magnetic axis, q_0, has been shown to be an effective way to get into this region. Since current drive techniques can provide control of the current distribution, it is useful to investigate the effect of configuration shape on the stability properties of systems with $q_0 > 1$. Comparison of configurations with different plasma cross sections requires a choice of the different parameters that are held fixed. In our study, we keep the values of q_0 and the poloidal flux between the magnetic axis and the plasma surface, $\Psi_{\text{edge}} - \Psi_0$, fixed. This flux is a measure of the effective poloidal field in the plasma. We fix the shapes of the pressure distribution $p(\Psi)$ and the toroidal field function $g(\Psi)$. The stability properties of differently shaped plasmas are surprisingly similar. However, none of them possesses a clear path from the first stable region to that of second stability. We are investigating the possibility of using a smaller plasma with a larger aspect ratio to find a route between the regions. This type of consideration may show that a machine like TFTR, which has a large circular vacuum vessel, adequate auxiliary power, good diagnostics, and access for introduction of field-shaping coils, would be an ideal device for study of configurational effects on high-β operation.

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Dependence of Faraday Shield Sputtering Rate on the Local Plasma Density[1]

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If plasma of density greater than about $10^9 - 10^{10}\mathrm{cm}^{-3}$ is present in the gaps of a Faraday shield in front of an ICRF antenna, and the Faraday shield is not perfectly aligned with the magnetic field of the tokamak, but is off by a small angle θ, then the plasma will rectify the RF electric field in the gaps, producing a DC potential between the plasma and the Faraday shield which is a substantial fraction of the RF potential V_{RF} across each gap. This DC potential can accelerate ions into the Faraday shield at energies of a few hundred eV, causing substantial sputtering of high-Z impurities[2] as observed in many ICRF experiments. The sputtering rate depends strongly on the angle at which the ions strike the Faraday shield. In the low density limit, $\omega_{pi} < \omega_{ci}$, the ions are strongly magnetized in the sheath; if polarization drift is neglected, they would strike the Faraday shield at an angle θ. At very high densities, $\omega_{pi}/\omega_{ci} > \theta^{-1/2}(eV_{RF}/T_e)^{3/4}$, the ions are completely unmagnetized in the sheath and strike the Faraday shield at an angle close to 90°; at intermediate densities the ion orbits are complicated, and the angle of incidence is difficult to calculate. When the polarization drift of the ions is taken into account, the angle of incidence is found to increase from θ by an amount $(\omega_{pi}/\omega_{ci})(eV_{RF}/T_e)^{-1/4}$ in the low density regime. This makes it possible to estimate the angle of incidence, and the sputtering yield, at all densities without the need to calculate complicated ion orbits. Furthermore, for a given density, there is a critical alignment angle θ below which the sputtering yield will be insensitive to θ. The origin of plasma in the Faraday shield gaps was also considered, and we note that ionization alone cannot account for it, except at rather high neutral densities,[3] about 10^{-3} torr. Otherwise some kind of RF-induced enhanced transport across the scrape-off layer is necessary, at a rate greater than Bohm diffusion. Transport by convective cells is one possibility.

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[1] Work supported by the U.S.D.O.E. under Contracts No. DE-AC02-78ET51013 and No. DE-FG02-88ER53263.

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RADIAL ELECTRIC FIELD AND ENHANCED CONFINEMENT REGIMES IN TOKAMAKS AND STELLARATORS*

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It is generally believed that the dominant loss mechanisms in toroidal systems such as tokamaks and stellarators are transport fluxes driven by turbulent fluctuations. In order to improve confinement in toroidal plasmas, one has to reduce anomalous transport fluxes. We suggest that a more negative value of E_r can reduce turbulent fluctuation amplitudes and thus improve anomalous transport fluxes. We assume that anomalous transport fluxes are intrinsically ambipolar. Note that there is no theoretical basis that prevents intrinsically ambipolar transport fluxes from depending on E_r. In tokamak neoclassical transport theory, transport fluxes do not depend on E_r, because they are driven by parallel friction force and $\vec{E} \times \vec{B}$ drifts are the same for both ions and electrons, not because they are intrinsically ambipolar. We conclude that even though anomalous transport fluxes are intrinsically ambipolar, they can depend on E_r but they cannot participate in determining E_r. For a given magnetic geometry, there is only one E_r profile which has no effect on fluctuation amplitudes and anomalous transport fluxes. Such an E_r profile corresponds to a rigid body angular rotation due to the $\vec{E} \times \vec{B}$ drift. For tokamaks, such a profile satisfies $d(E_r q/r)/dr = 0$; for stellarators, it satisfies $d(E_r/r)/dr = 0$. From the kinematic point of view, the shear of angular velocity changes the thermodynamic forces. In order to maintain intrinsic ambipolarity at the stationary state, the fluctuation spectrum has to change. From the dynamic point of view, shear of the angular velocity changes the decorrelation time. An analytic theory will be presented to discuss the effects of E_r on the fluctuation spectrum, with special emphasis on the q dependence in tokamak geometry. There are several experimental observations in tokamaks and stellarators which indicate that a more negative value of the radial electric field E_r can improve plasma confinement. We have developed an improved model for the H-mode. We have also extended our model to describe other improved confinement regimes observed in tokamaks and stellarators.

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The "Dynamic Layer Model" for L- to H-mode transition*

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A "Dynamic Layer Model" for L- to H-mode transition is proposed. This model is a combination of the edge bifurcation model[1] and the microtearing model[2] and is characterized by dynamic interplay between the core plasma, scrape-off layer (SOL), and divertors. In this model, the L-H transition can be described qualitatively as follows:

1. At L-mode, plasma profiles are unstable to microtearing instability (other instabilities may also be present).

2. Core heating (or a sawtooth crash) raises T_e near the edge of core. This in turn lowers ν_{ei}/ω_{*e} and makes microtearing modes less unstable in that region.

3. Since the edge of the core plasma is more stable to microtearing instability, the heat flow to the divertor chambers decreases; consequently, the divertor chambers go into a higher recycling state. More neutrals are ionized there. The ionized particles flow across the separatrix and build up the density.

4. The sudden buildup of n_e just inside the separatrix makes microtearing modes more stable there. This acts as a positive feedback to step 3 and the edge plasma rapidly transits into a state stable to microtearing modes, with high-recycling divertors. This state is the H-mode.

During the transition, the divertors provide storage of neutrals, ready to be used for the sudden buildup of n_e. Limiter H-mode is possible if such a storage of neutrals (near the wall) exists. Although the H-mode is stable to microtearing instability, other instabilities may still exist. At H-mdoe, particles continue to flow in from divertors and n_e keeps increasing, until an edge localized mode (ELM) occurs.

We will first investigate the microtearing stability properties of the plasma at H-mode. More detailed comparison with experiments can than be made. The edge plasma plays a crucial role in this model. Results on research along this line will be reported.

* work supported by a Center of Theoretical Physics fellowship at the Physics Department of the University of Maryland, and partially by Department of Energy.

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Heat Pulse Propagation with Drift-Wave-Turbulence Models for Thermal Conductivity*

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In view of the outrageously early deadline this abstract is less than complete. The idea is to linearize pertubations in the heat conductivity equation about an equilibrium which governs the time-average (including sawteeth) heat conductivity problem. A variety of drift-wave/η_i expressions for the thermal diffusivity are used. Steady-state temperature and thermal diffusivity profiles are obtained which are well-behaved, but sensitive to precise boundary conditions. Linearized sawteeth are represented by an abrupt positive heat pulse superposed on a weak inward heat flow so that the time-average perturbed heat flow vanishes as it must. Density and current density profiles are held fixed. Heat pulse propagation results with and without perturbations to the equilibrium conductivity (which adds an outward advective velocity) will be presented. I am as interested in what they will be as you.

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Alpha Particle Microinstabilities and Stabilization of MHD Modes

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In ignited plasmas high frequency waves can be destabilized by alpha particles. These waves exert a time averaged force, ponderomotive force, on the plasma, thus modifying its MHD stability properties. To illustrate this phenomenon, the Alfven-ion cyclotron instability driven by a loss cone distribution of alpha particles[1] is considered. It is seen that the ponderomotive force of the fastest growing wave has a stabilizing influence on the flute mode. The saturated fluctuation level is estimated using the quasilinear relaxation and the resonance broadening as the saturation mechanisms. Saturated wave amplitudes are found sufficiently large to stabilize the flute mode for the thermonuclear mirror reactor range of parameters.
Supported by U.S. DOE Grant no. DE-FG02-88ER53264.

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SHERWOOD THEORY MEETING 1989

Numerical Simulations of the Ion Pressure Gradient Driven Turbulence*

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Recent experimental study[1] in the TEXT tokamak indicates that the ion pressure gradient driven (η_i) instability plays an important role to determine the global energy confinement time of the plasma. In this presentation, we will provide results of numerical simulations of the collisional ion pressure gradient (η_i) driven turbulence and derive the scaling of the associated heat transport. Here a set of the equations of the η_i-mode with nonzero (perpendicular and parallel) viscosity is solved numerically in a sheared slab geometry using a nonlinear initial value code, in which a finite difference scheme in the x-direction (which corresponds to the direction of the minor radius) and Fourier component representation in the other two directions are employed. In this work, we will particularly clarify the compressibility effect $\Gamma p(\nabla \cdot \mathbf{v})$ (where p is the ion pressure and Γ is the ratio of the specific heats) on the mode, which tends to stabilize the mode and gives a more realistic threshold value of $\eta_i\,(= d\ln T_i/d\ln n)$. In order to examine linear properties of the η_i-mode, we also solve the dispersion relation using a shooting code. This result is compared to our theoretical prediction of the linear growth rate of the η_i-mode $\gamma = \mathrm{s}\left(1 + \eta_i - \frac{3}{4}\Gamma\right)|\omega_{*e}|$ obtained from a perturbation theory in a small shear limit, where s is the shear parameter.

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

Study of Limiter/Separatrix Effects on τ_p*

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On a number of tokamaks (TEXT, ISX-B, DITE) it is observed that the particle confinement time, τ_p, depends on the poloidal location of the plasma-limiter contact point. Similarly, the position of the x-point in diverted tokamaks seems to play a role in H-mode transitions. We try to explain those observed poloidal asymmetries by studying the drift of ion bananas in the edge of the plasma as it is directed towards or away from the contact point or x-point.

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

STABILITY ANALYSIS OF FREE BOUNDARY MODES FOR ATF

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By thorough revision of the BETA code a new MHD code called BEFREE has been developed to test the stability of low order free boundary modes in stellarators. Artificial viscosity has been added to the free boundary condition to assure adequate convergence of the finite difference method, and a spectral representation has been applied to the equations at the magnetic axis that produces a robust algorithm. The energy can now be calculated to ten or more significant figures on any fixed mesh, and convergence studies provide reliable growth rates from the usual second minimization associated with a trial mode.

As predicted by two-dimensional theory, the free boundary modes of three-dimensional stellarators are found to be generally more stable than internal modes of higher order. However, the $m = 1$, $n = 0$ free boundary mode of a two-dimensional ATF configuration is only stable for average β below 5%. Comparable modes for a Heliac of moderate aspect ratio have β limits exceeding 7%. Runs of the new code suggest that while ATF and Helias equilibria can be stabilized by shifting the magnetic axis outwards, there is then a risk that the magnetic surfaces deteriorate. A more detailed account of these results will be presented at the stellarator workshop in Oak Ridge next week.

Studies of Axisymmetric Modes in Tokamak Plasmas with Active and Passive Feedback *

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Deformable tokamak plasmas with highly shaped cross-sections are susceptible to axisymmetric ($n = 0$) instabilities. Complete stabilization of these modes may be possible by a combination of resistive walls and an active feedback system. Previous studies have shown, however, that both the stability of the system and the nature of the eigenmodes can depend strongly on the details of the active feedback system.[1] For example, it was found that for certain locations of the flux detection loops around the plasma cross-section the active feedback system was unable to completely stabilize the axisymmetric plasma motion regardless of the feedback gain.

To study these effects we are developing a plasma stability code that includes passive resistive conductors and an active feedback system within the plasma-vacuum model. These modifications will not fit into the framework of the self-adjoint δW formulation. Therefore we use the non-ideal, non-variational stability code NOVA.[2] We have modified the vacuum calculation of the NOVA code to include resistive passive conductors. We will also add the ability to account for currents from active feedback coils based on poloidal flux measurements. Details of these modifications and the results from some test cases will be given.

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1989 International Sherwood Theory Meeting

ANALYTIC STUDIES OF ICRF HEATING*

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ABSTRACT

Recent advances [1,2] in analytic theory of dissipative coupling for ICRF are limited to either pure second-harmonic heating [2], or to D(H) minority heating [1] which includes D or H second-harmonic heating as a special case. In the present work, the coupling theory [1] is extended to cover the imporant case of D-T-3He heating, for arbitrary species concentration ratios.

It was found that a fourth order in k-perp dispersion relation for D(3He) obtained from a straight forward small k-perp expansion does not reproduce the full 3x3 dispersion relation. An erroneous resonance in the ion-Bernstein branch appears between the fast-Alfven wave cutoff and the minority fundamental harmonic; an erroneous mode with very large k-perp appears on the low field side. These are purely artifacts of the the k-perp expansion. In D(H) and the other cases the erroneous singularity occurs well outside of the coupling region and can be ignored. In the D(3He) case however the singularity must be regularized. A generalized method has been developed to obtain the correct 4th order in k-perp dispersion relation for any scheme.

Excellent agreement with the results from the Imre-Weitzner boundary layer code is obtained.

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Investigation into Resistive Drift Ballooning Modes in a Poloidal Divertor Tokamak*

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Code modifications are under way to study the linear and nonlinear evolution of resistive drift ballooning modes in a poloidal divertor tokamak. The physics model employed is an extended version of the high beta, large aspect ratio reduced resistive MHD equations for tokamaks including the effects of electron diamagnetic drift, compressibility and thermal conduction. The set of equations are solved as an initial value problem. All the dependent variables are finite-differenced in the radial direction and Fourier-analyzed in both poloidal and toroidal directions. An initial axisymmetric MHD equilibrium is generated by relaxing the plasma into the lowest energy state subject to the flux conservation constraints. We first examine such modes in a non-diverted tokamak and then focus on an open divertor configuration with a moderate noncircularity. Preliminary results and their implications for the H-mode and edge localized modes (ELM's) will be discussed.

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Electron Cyclotron Wave Propagation and Transport Studies in the Compact Ignition Tokamak*

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The possibility of heating the Compact Ignition Tokamak (CIT) with electron-cyclotron power at 280 GHz (fundamental cyclotron resonance) is examined by analytic and computational means. Ray tracing and absorption calculations, performed with the TORCH code, indicate that efficient single-pass absorption of the O-mode polarization, which is accessible from the low-field side for frequencies above the fundamental, can be accomplished by scanning the angle of injection of the microwave power from 60° to 90° relative to the toroidal magnetic-field direction as the field intensity is ramped from 7.5 to 10 T. The relevant range of plasma parameters studied varied from central densities from 2 to 8 $\times$ $10^{20}\mathrm{m}^{-3}$ and central temperatures from 5 to 20 keV. The power absorption profile is obtained from the ray tracing and absorption packages and used as an input to a transport code.

We have used a version of the combined equilibrium and transport code BALDUR$1\frac{1}{2}$D to simulate some important aspects of the ECH heating scenario for CIT. We have assumed that the electron heat flux can be expressed as the sum of an outward conduction term and an inward heat pinch with both terms being proportional to a modified form of Coppi-Mazzucato-Grüber thermal diffusivity which can reproduce L or H mode experimental results in the auxiliary heating regime. The combination of inward and outward fluxes seeks to enforce a "canonical" profile shape. Anomalous ion thermal transport has been taken to be proportional to that of the electrons (in addition to a neoclassical contribution). The ECH ray tracing results have been incorporated by representing the power absorption as $P(\rho) \propto \exp[-(x(\rho) - x_0)^2/225]$ where $x(\rho)$ is the half-width of a flux surface in cm and x_0 is the location of maximum absorption. This model has been used to study the effects of ECH heating during the ramp phase of CIT where the current, toroidal field, and density are all less than their flat-top values and absorption is either on or off-axis. We have also investigated the approach to ignition of a plasma with flat-top parameter values and on-axis absorption. We have examined the individual effects of heat conductivity magnitudes, sawteeth, profile consistency, and density profile in achieving ignition in CIT. Results from these simulations will be presented.

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MODELING OF FLUCTUATIONS IN THE EDGE OF THE TEXT TOKAMAK*

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Detailed modeling of Text edge plasmas has been undertaken using the 3D nonlinear fluid computer code KITE,[1] which solves a set of fluid equations in cylindrical geometry. We have first concentrated on resistivity-gradient-driven turbulence, since it is the prime candidate to explain some of the experimentally observed features of the turbulence.[2] Impurity dynamics are included in our model through a $Z_{\rm eff}$ evolution equation.[3] Impurity radiation[4] is incorporated in the electron temperature evolution equation. The effect of the diamagnetic drift frequency and of a sheared radial electric field[5] have been invoked to explain the observed broad frequency spectrum of the electrostatic fluctuations and are presently being implemented in the model.

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ACCESS TO SECOND STABILITY IN ATF*

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The Advanced Toroidal Facility (ATF) was designed to have stable access to the second stability regime. For the design conditions, this access should occur at beta values about $\beta_0 \approx 5\%$. In its initial phase of operation, the ATF plasma minor radius and the edge rotational transform, ι_a, were reduced by field errors, (which have been repaired). this reduction of radius and ι_a caused a large increase on the Shafranov shifts and, as a consequence, a reduction in the beta value needed to access the second stability regime. From the low-n and high-n stability analysis using the experimentally measured profiles, the threshold to second stability was found to be as low as $\beta_0 \approx 1.0\%$. The beta values reached in the experiment, up to $\beta_0 \approx 3.0\%$, are well above this threshold value. The magnetic fluctuation measurements showed reduction of the fluctuation level for $\beta_0 \geq 1\%$. These fluctuation levels are in reasonable agreement with the theoretical calculations based on the resistive pressure-gradient-driven turbulence and support the evidence that ATF has already operated in the second stability regime.

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Ballooning β Threshold for the Second Region Of Ideal MHD Stability in Tokamaks†

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The β required to reach the second region of stability to high-n ballooning modes is found for finite aspect ratio tokamaks of various cross-sectional shapes and safety factor profiles. Equilibria with pressure profiles, $p(\psi)$, that are marginally stable to the second region at each flux surface are generated numerically by a two-dimensional equilibrium code that iterates with a high-n ballooning solver. This marginal stability constraint eliminates $p(\psi)$ as an independent variable in the calculation producing 'optimized' profiles. The parameters of the analysis are then reduced to the tokamak geometry and the safety factor profile, $q(\psi)$, specified as $q(\psi) = q_o + (q_a - q_o) \psi^{\alpha_q}$, where ψ is the normalized poloidal flux, and q_o, q_a are the axis and edge safety factors, respectively. Both $p(\psi)$ and $q(\psi)$ are restricted to be monotonically increasing functions of ψ. The primary response variables considered are the basic plasma equilibrium figures of merit, β and $\varepsilon\beta_p$, whose marginally stable second region values are denoted by β_2 and $(\varepsilon\beta_p)_2$. The ranges of the predictor variables used in the analysis are $1.5 \leq A \leq 15$, $1.01 \leq q_o \leq 2.5$, $1.1 \leq q_a \leq 20.1$, $1.1 \leq \alpha_q \leq 4.0$, $0.0 \leq \kappa \leq 2.5$, and $0.0 \leq \delta \leq 1.0$ where κ and δ are the plasma elongation and triangularity, respectively.

For the circular outer boundary shape, β_2 decreases with increasing aspect ratio and increasing q_o, except for high q_o and low aspect ratio, where this trend reverses. At large A, $(\varepsilon\beta_p)_2$ is independent of aspect ratio, whereas finite aspect ratio corrections cause $(\varepsilon\beta_p)_2$ to increase or decrease at low A, dependent on the value of q_o. Increasing the elongation of the outer flux surface with $\delta = 0$ increases β_2. Finite triangularity coupled with $\kappa > 0$ (Dee shaping) enhances stability, thereby decreasing β_2 and $(\varepsilon\beta_p)_2$. In general, increasing q_o above unity and reducing α_q each individually decrease β_2 and $(\varepsilon\beta_p)_2$. Increasing q_a decreases β_2 except at sufficiently small (q_a / q_o) when no unstable region is found ($\beta_2 = 0$). Low aspect ratio, elongated plasmas exhibit the most sensitive dependence of β_2 on the remaining global parameters. Simple analytic models are presented which reproduce the scaling of the marginally stable second region values of $\varepsilon\beta_p$ for circular outer boundary shape. The effects of Shafranov shift and finite aspect ratio are considered. A comparison is made with previous (S,α) model estimates of the second region stability boundary at low[1] and high[2,3] shear.

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SHERWOOD THEORY MEETING 1989

Resistive Tearing Instability with Equilibrium Shear Flow*

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We study the effect of an equilibrium sheared velocity profile on resistive tearing instability using the boundary layer approach. Both the classical tearing mode, which has a growth rate that scales as $S^{-3/5}$, and the long wavelength mode ($\Delta' \to \infty$), which has a growth rate that scales as $S^{-1/3}$, are treated. Here S is the usual ratio of the resistive diffusion and Alfvén times. Three ranges of velocity shear are considered within the internal resistive layer: $\Sigma \ll 1$, $\Sigma \approx 1$, $\Sigma \gg 1$, where Σ is the ratio of the velocity shear to the magnetic shear. Also, the effect of flow on the exterior problem is discussed. For small velocity shear, the scaling of γ_c, the growth rate of the classical tearing mode, and γ_L, the growth rate of the long mode, remain unchanged. But γ_L is decreased. In the case where $\Sigma \approx 1$, the scaling of the long mode is unchanged, but the classical mode now scales as $S^{-1/2}$, with alteration to the magnitude of the growth rate. Finally for large shear, both modes are stable with damping rates that scale as $S^{-1/2}$. Comparison to the works of Einaudi and Rubini,[1] Hofman,[2] and Paris and Sy[3] will be made.

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NONLINEAR EFFECT OF WAVES IN THE ION CYCLOTRON RANGE OF FREQUENCIES ON ION TEMPERATURE GRADIENT DRIFT MODES

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Abstract

A dispersion relation is derived for ion temperature gradient-driven drift waves nonlinearly modified by sideband interactions caused by a power source in the ion cyclotron range of frequencies (ICRF). Solutions of the dispersion relation show that mode stability characteristics can be significantly affected by moderate ICRF power in low density and temperature tokamak operating regimes using certain short wavelength ion Bernstein waves. Conclusions of this work are compared to those of a previous study of ICRF sideband coupling to tokamak trapped electron modes.

CALCULATION OF SATURATED TEARING MODES USING THE PIES EQUILIBRIUM CODE*

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The PIES three-dimensional equilibrium code [1] calculates equilibria with islands, for specified plasma current and pressure profiles. The use of PIES as a stability code is demonstrated by using it to calculate saturated tearing modes in tokamak geometry. A recent interesting analytic calculation of Zakharov [2] provides a convenient benchmark test for this code capability.

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Toroidal Field in Field-Reversed Configurations During Translation*

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Toroidal field has been measured in the FRX-C and LSM Field Reversed Configuration (FRC) experiments while the plasma was being translated. There are no measurements of toroidal field during the phase of the experiment occuring after formation but before translation. Several previous studies[1,2] have investigated the generation of toroidal field during the formation phase. This report presents the results of the initial phases of research on the generation of toroidal field during translation. Specifically, the following question is addressed: Given an FRC which is initially at rest without a toroidal field and assuming kinetic ions, Hall terms in Ohm's law, and axisymmetry for all times, under what condition will a toroidal field of the correct magnitude develop? One application of this would be whether the measured toroidal fields mentioned in the first sentence could be induced during translation of an FRC initially having no toroidal field, or whether a toroidal field must be present initially in order to be consistent with the observations.

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Nonlinear Tearing Modes in the Reversed Field Pinch*

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ABSTRACT

Thanks to a large body of experimental and theoretical work, nonlinear tearing modes in the tokamak are relatively well understood. To develop a predictive understanding of the physics of this type of phenomena, however, it is necessary to repeatedly and continually meet the challenge of new plasma regimes. The Reversed Field Pinch is one such new regime. A basic question for the Reversed Field Pinch is: Do phenomena similar to Tokamak nonlinear tearing modes occur?

The theory of nonlinear tearing modes has several levels. At the most basic level it is the theory of bifurcated equilibrium states with magnetic islands. The traditional method of solving the nonlinear equilibrium equation, simple iteration, does not converge for equilibria with helically symmetric magnetic islands. [1] Newton's method has been implemented to solve for helically symmetric equilibria. Such calculations for the Reversed Field Pinch will be discussed. Often, nearby helical states are present for all zero-beta unstable modes, since these modes are ideally stable and hence similar to Tokamak $m > 1$ tearing modes. The island width is strongly dependent on conducting wall position. An interesting result of these equilibrium calculations is the occurence of magnetic wells in the island interiors.

At the next level of completeness, the theory must account for the time evolution of the island. A resistive evolution picture assuming weak magnetic stochasticity, self consistently caused by current filamentation [2] and superimposed on the helical structure, will be discussed. The time dependence in such a model is different from the time dependence of evolution when there are magnetic surfaces. The question of time dependence in various models incorporating stochasticity will be discussed.

Finally, the experimental evidence for saturated tearing modes in the Reversed Field Pinch will be discussed. Fluctuations are always present, with a greater or lessor degree of coherence. Quite coherent signals are observed at times in SXR arrays and seem consistent with an internal rotating $m = -1$ island. For certain high Θ ramped discharges, signals from a wide variety of diagnostics show a large coherent $m = 0$, $n = 1$ structure. This structure is particularly interesting in that it seems to confine a very large particle density.

* Work performed under the auspices of the USDOE

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SECOND-STABILITY MHD EQUILIBRIUM CANDIDATES FOR A REACTOR*

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ABSTRACT

This paper reports on current progress in finding a viable candidate for an MHD equilibrium configuration with significantly high beta (~20%) that might be used in a tokamak reactor. Viable means that the current goes to zero at the plasma boundary; the profiles (pressure, $F \equiv RB_t$, safety factor) are of a similar nature to those found in tokamak experiments or which might be expected if profile tailoring by current drive were available; the profiles do not have excessively high gradients; and the equilibrium is theoretically stable to known modes. There does not seem to be an equilibrium fitting this description in the literature.

Even though it is possible to enter the second-stability region at lower values of beta, it seems to be difficult to continue to raise beta to the above level. Part of the problem is the appearance of convergence limits to the equilibrium (but not necessarily stability) calculation as the current gradients become large. The attractive equilibria for the above criteria seem to be near these limits, and much of the current work has focussed on validating the results of the codes near these limits.

These problems will be discussed, and the most attractive of the equilibria found to date will be presented.

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SCATTERING FROM MAGNETIC FLUCTUATIONS IN TOKAMAKS

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Abstract

Plasma transport can be strongly effected by magnetic field fluctuations. It is of considerable interest to be able to deduce some information on the magnetic fluctuation spectrum by scattering. Following a suggestion by Bretz[1], we calculate the differential cross section for the transformation of O-modes into X-modes due to plasma fluctuations. The idea is that for certain scattering directions, it can be shown that there can be no conversion from O-mode to X-mode if only density fluctuations are present. This will then allow a study of the O → X mode transformation because of magnetic fluctuations.

The general scattering theory of Sitenko[2] must be corrected to include geometric effects that occur because of the directional difference between phase and group velocities[3,1] in the plasma. We investigate the scattering/mode transfomation that arises from density fluctuations and from magnetic flucutatons in the 10-150 kHz range.

Work supported by the Department of Energy

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2. A. G. Sitenko, 'Electromagnetic fluctuations in plasma' (1967)
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Three-dimensional Kinematic Reconnection in the Presence of Field Nulls and Closed Field Lines*

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This paper investigates three-dimensional reconnection of magnetic fields with nulls ($\mathbf{B} = 0$) and closed field lines. We review the geometry of magnetic fields with nulls, focusing on the important structures—the γ lines and Σ surfaces. Configurations with a pair of type A and B nulls can have reconnection across the null-null lines—field lines that join the two nulls. We also review *magnetostatic reconnection*, in which the specified magnetic field is time independent and the electrostatic potential, computed from ideal MHD, is constant along field lines. For configurations with one or two nulls, potential mapping along field lines gives essential singularities and step function discontinuities, whose structure indicates properties of reconnection in nonideal MHD. We generalize magnetostatic reconnection to specified time-dependent magnetic fields and call this approach *kinematic reconnection*. The resulting field line velocity $\mathbf{v}_\perp = \mathbf{E}\times\mathbf{B}/B^2$ may exhibit singularities, which are again the signatures of reconnection associated with nonideal effects. Two-dimensional models (with $\partial/\partial z = 0$) with X-point structures are used to illustrate this approach. Singularities of field line velocities are found on the separatrix, in addition to those along the X-line. The singularities found on the separatrix are purely kinematic in origin and are not caused by incompressibility on the one hand or by shocks on the other. Their presence agrees qualitatively with the behavior seen in simulations. For a class of three-dimensional models, the singularities in the field line velocity have distinct characteristics for models with and without nulls, suggesting different physics for the two cases. Reconnection for three-dimensional models without nulls (closed field line) is qualitatively the same as two-dimensional models (with $\partial/\partial z = 0$) with a nonzero constant B_z. For models with a pair of A and B nulls, singularities appear on the Σ surfaces, the γ lines, the A-B line, and at the nulls, with fractional power law dependences. These singularities reveal the following picture of three-dimensional reconnection: field lines going into reconnection are forced to become one of the γ_{B}-$\overline{\mathrm{BA}}$-γ_{A} lines, and field lines coming out of reconnection are pulled from these lines. Kinematic reconnection for configurations with two null-null lines is similar: each of the A-B lines serves as a separate bridge for the field lines to reconnect. The inductive electric field along the A-B lines is the driving force of the whole process.

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"Revised Stability for the Z-pinch, and Prediction of a Class of Magnetostatic Plasma Oscillations".

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Abstract: A model for the Z-pinch which is based upon the mutual interaction of current filaments successfully predicts the Bennett relation, and experimentally measured parameters such as the charge density distribution. Further, the same model describes the collapse of the dynamic pinch and predicts a theoretical pinching time which is substantially the same as that given by the "snowplough" model. The experimentally observed transverse and helical oscillations, forbidden by the usual stability analysis, are described very accurately, both qualitatively, and quantitatively, by the current-fibre model. A general class of "magnetostatic plasma oscillations" are predicted to exist in any plasma current as the low-frequency relativistic analogue of the electrostatic plasma oscillations. These large-scale collective motions have characteristic frequency $\omega = J(\mu/2\rho_m)^{1/2}$, and period which is of the order of the transverse ion-acoustic time $2a/C_s$, or the MHD time $2a(\mu\rho_m)^{1/2}/h(a)$. Some of the observed instabilities of a plasma may be interpreted as large-amplitude plasma oscillations driven by the confining energy itself.

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The Effect of the Ideal Kink Mode on Sawtooth Behavior*

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Using a set of low beta toroidal reduced MHD equations, we study the effect of the ideal kink mode (current driven) on sawtooth behavior. This mode is present when the q-profile is non-monitonic with off-axis minimum approximately equal to one.[1] For the first time, sawtooth behavior is studied at realistic values of the resistivity $[\eta(=1/S) = 3 \times 10^{-8}]$ at which the ideal MHD modes become important.

1. M.N. Bussac, K. Lerbinger, R. Pellat, and M. Tagger, in *Plasma Physics and Controlled Nuclear Fusion Research 1986* (Proc. 10th Int. Conf., Kyoto, Japan 1986), Vol. II, IAEA, Vienna (1987) 17; R.J. Hastie, T.C. Hender, B.A. Carreras, L.A. Charlton, and J.A. Holmes, Phys. Fluids **30**, 1756 (1987).

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New Particle Algorithms for Fusion Applications*

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Recently developed δf algorithms[1] have been applied to the magnetic electron drift-kinetic and ion gyrokinetic equations. These are very advantageous for fusion applications: 1) They provide large noise reductions (compared to a standard code) for the same number of particles; (2) They can easily be made partially implicit allowing large time steps. Accuracy, stability, and economy of these algorithms are evaluated for the kinetic equations above in sheared slab.

Accuracy is checked linearly by detailed comparison of frequency and growth rate with results of eigenmode codes. Nonlinearly, accuracy is checked by comparison with a finite difference code which treat the distribution function by standard fluid techniques. Conservation laws are also checked.

The magnetic drift electron code is shown to be accurate both linearly and nonlinearly for simulations of tearing modes with fusion parameters, but without equilibrium temperature gradients. Stable operation is also demonstrated for $k_{\|}v\Delta t \gg 1$. Equilibrium temperature gradients produce accuracy degradation in the long-time limit which is being investigated.

A similar algorithm has been applied to the ion gyrokinetic equations. Field computations are performed by a novel scheme accurate for $k_{\perp}\rho_i \gg 1$. Preliminary linear tests are favorable; more detailed linear and nonlinear demonstrations will be presented.

1. Institute for Fusion Studies Report #360, "Particle Simulations with Greatly Reduced Noise," M. Kotschenreuther.

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