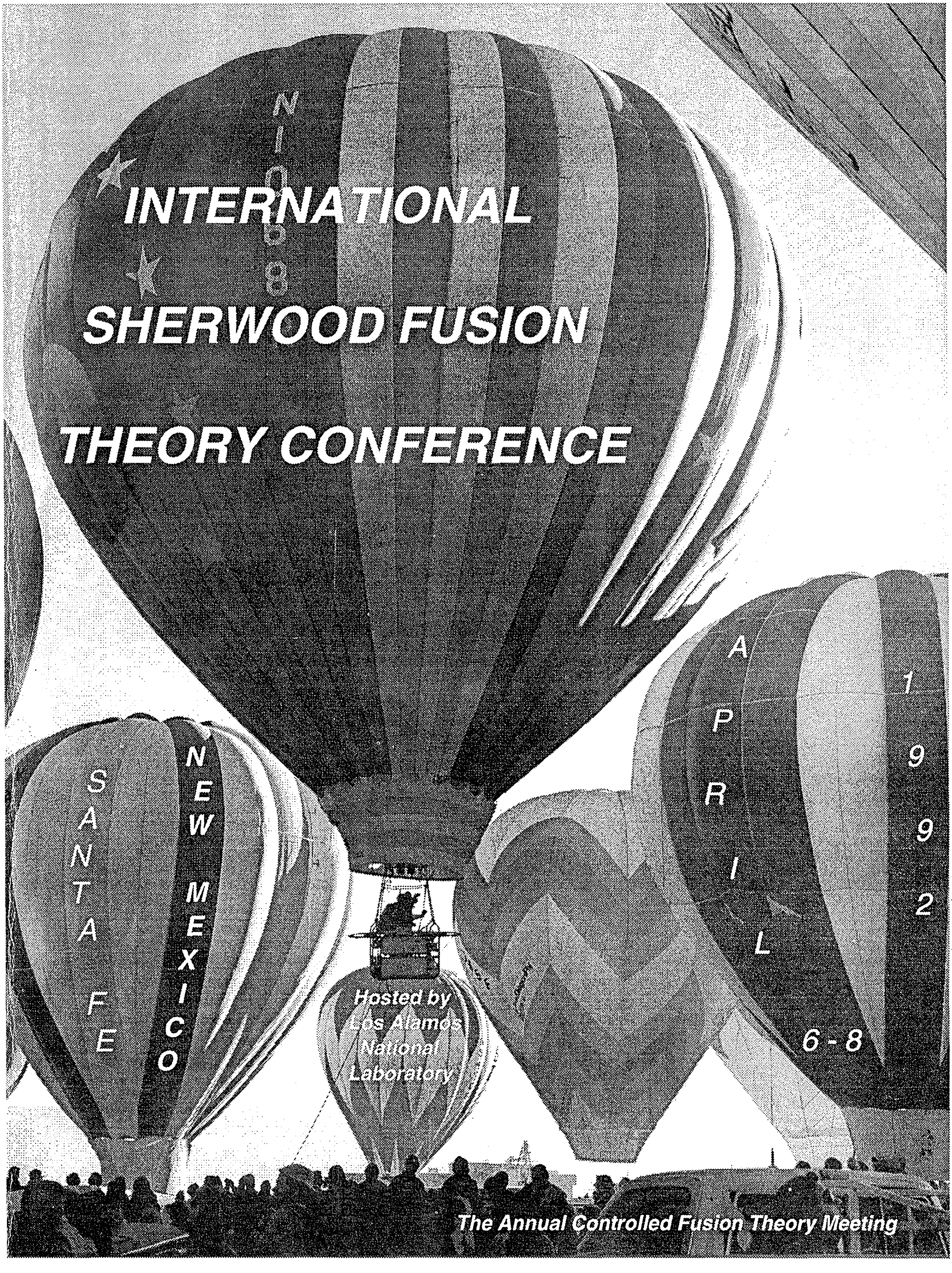
Sherwood '92


INTERNATIONAL
SHERWOOD FUSION
THEORY CONFERENCE
SANTA FE
NEW MEXICO
APRIL
1992
6 - 8
Hosted by
Los Alamos
National
Laboratory
The Annual Controlled Fusion Theory Meeting

Saralyn Stewart

1992
INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

APRIL 6-8, 1992
SWEENEY CONVENTION CENTER
SANTA FE, NEW MEXICO

Under the auspices of

LOS ALAMOS NATIONAL LABORATORY
Los Alamos, New Mexico

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LA-UR-92-761

GENERAL INFORMATION

* 214 papers were submitted, of which 14 were selected for oral presentation.

* The Review papers will be presented in the Sweeney Convention Center, main floor, Monday and Tuesday mornings beginning at 8:30 a.m.

* Oral papers will be presented in the Sweeney Convention Center, main floor, Monday and Tuesday mornings at 9:30 a.m. and Wednesday morning at 8:30 a.m.. Each talk will be 25 minutes in length plus 5 minutes for discussion.

* A special session on "Aid to Physicists of the Former Soviet Union" will be held Monday afternoon, April 6, at 1:00 p.m. in room 2 on the balcony level of the Convention Center.

* An open discussion on Fusion Computing Needs with the Fusion Computing Council will be held on Monday, April 6, from 5:30-6:30 p.m. in room 2 on the balcony level of the Convention Center.

* Poster sessions will be held in rooms 1,3, and 4 on the balcony level of the Convention Center, Monday afternoon from 2:00-6:00 p.m., Tuesday evening from 8:00-10:00 p.m. and Wednesday morning from 10:30 a.m-12:30 p.m.

* A welcome reception will be held during registration on Sunday evening, April 5 at the El Dorado Hotel, main lobby area, from 6:00-10:00 p.m.

* A companion's breakfast will be held on Monday morning at 9:00 a.m. in the Old House Restaurant at the El Dorado Hotel.

* Refreshments will be served in the lobby area of the Sweeney Convention Center, consisting of coffee and tea, Monday through Wednesday mornings at 9:30 a.m. and beer and soft drinks Monday afternoon at 3:00 p.m. and Tuesday evening at 8:00 p.m. on the balcony level.

* Requests for special meetings should be made with Saralyn Stewart at the Conference Registration Desk.

1992 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE
SWEENEY CONVENTION CENTER, SANTA FE, NEW MEXICO
APRIL 6-8, 1992

SCHEDULE

REGISTRATION -
El Dorado Hotel, Lobby area
Sunday, April 5 - 6:00-10:00 p.m.

Sweeney Convention Center
Monday, April 6 - 7:45 a.m.-5:00 p.m.
Tuesday, April 7 - 8:00 a.m.-12:00 p.m. and 8:00-10:00 p.m.
Wednesday, April 8 - 8:00 a.m.-10 a.m.

ORAL AND POSTER SESSIONS
Review and Oral Talks - Main Floor, Convention Center
Posters - Balcony Level, Rooms 1, 3 & 4

		Monday	
8:20 a.m.		Welcome	Alan Glasser, Local Chairman
8:30 a.m. - 9:20 a.m.	1A	Review Talk	Alan Gibson
9:30 a.m.-12:00 p.m.	1B	Oral Session	
1:00 p.m. - 2:00 p.m.	1E	Special Session: Aid to Physicists of the Former Soviet Union	
2:00-4:00 p.m.	1C	Poster Session	
4:00-6:00 p.m.	1D	Poster Session	
		Tuesday	
8:30 a.m. - 9:20 a.m.	2A	Review Talk	Allan N. Kaufman
9:30 a.m. - 12:00 p.m.	2B	Oral Session	
12:00 - 8:00 p.m.		FREE TIME	
8:00-10:00 p.m.	2C	Poster Session	
		Wednesday	
8:30-10:30 a.m.	3B	Oral Session	
10:30 a.m.-12:30 p.m.	3C	Poster Session	

Monday Oral Schedule

8:20 a.m.		A. Glasser, Local Chairman, Opening Remarks
8:30 a.m.	**1 A**	Chair: J. Van Dam A. Gibson, *The Controlled Release of Fusion Energy Using the Deuterium/Tritium Reaction in JET*
Oral Papers	**1 B**	Chair: E. Hameiri
9:30-9:55 a.m.		F. Porcelli et al., *Resistive Internal Kinks and ICRF Phasing Current Drive*
10:00-10:25 a.m.		S.E. Parker et al., *3D Toroidal Gyrokinetic Simulation of Ion Temperature Gradient Driven Turbulence*
10:30-10:55 a.m.		A. M. Dimits et al., *Nonlinear Particle and Fluid Simulations using Quasi-Ballooning Coordinates*
11:00-11:25 a.m.		H. Ye et al., *Map Model for Nonlinear Alpha Particle Interaction with Toroidal Alfvén Eigenmodes*
11:30-11:55 a.m.		D.A. Spong et al., *Fluid/Kinetic Models for Shear Alfvén TAE Instabilities in Tokamaks*

Tuesday Oral Schedule

8:30 a.m.	**2 A**	Chair: W.M. Nevins A.N. Kaufman, *New Mathematical Methods for Linear Plasma Problems*
Oral Papers	**2 B**	Chair: G. Morales
9:30-9:55 a.m.		N.J. Fisch et al., *The Interaction of Energetic Alpha-Particles with Intense Lower Hybrid Waves*
10:00-10:25 a.m.		C.T. Hsu et al., *Energetic Alpha Particle Induced Bootstrap Current*
10:30-10:55 a.m.		J.M. Dawson et al., *On the Possibility of a Steady State Tokamak Maintained by Bootstrap Current Drive Alone*
11:00-11:25 a.m.		R.H. Cohen et al., *Electron-Temperature-Gradient Turbulence in Tokamak Scrape-Off Layers*
11:30-11:55 a.m.		L. Sugiyama et al., *Physics Principles of Ignition Experiments*

Wednesday Oral Schedule

Oral Papers	**3 B**	Chair: E. Tracy
8:30-8:55 a.m.		G.M. Zaslavsky, *Anomalous Kinetics of incomplete Chaos*
9:00-9:25 a.m.		X. Su et al., *Nonlinear Drift Wave Structures in a Sheared Magnetic Field*
9:30-9:55 a.m.		A. Fruchtman et al., *Nonlinear Skin Phenomena in (almost) Collisionless Short-duration Plasmas*
10:00-10:25 a.m.		G.P. Zank et al., *The Theory of Nearly Incompressible Magnetofluid- Dynamics*

1992 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

Sweeney Convention Center, Sante Fe, NM
April 6 - 8, 1992

REGISTRATION - El Dorado Hotel, Lobby area
Sunday, April 5 - 6:00pm - 10:00pm

REGISTRATION - Sweeney Convention Center
Monday, April 6 - 7:45am - 5:00pm
Tuesday, April 7 - 8:00am - 12:00pm, 8:00pm - 10:00pm
Wednesday, April 8 - 8:00am - 10:00am

MONDAY MORNING

WELCOME - 8:20am - Alan Glasser, Local Chairman

1A Review Talk
8:30am - 9:20am
Presiding: J. Van Dam

1A1. The Controlled Release of Fusion Energy Using the Deuterium Tritium Reaction in JET. Team. JET and A. Gibson.

1B ORAL SESSION
9:30am - 12:00pm
Presiding: E. Hameiri

1B1. Resistive Internal Kinks and ICRF Phasing Current Drive. F. Porcelli, A. Cherubini, and A. Taroni.
1B2. 3D Toroidal Gyrokinetic Simulation of Ion Temperature Gradient Driven Turbulence. S. E. Parker and W. W. Lee.
1B3. Nonlinear Particle and Fluid Simulations using Quasi-Ballooning Coordinates. A. M. Dimits, T. J. Williams, and J. A. Byers.
1B4. Map Model for Nonlinear Alpha Particle Interaction with Toroidal Alfven Eigenmodes. H. Ye, H. L. Berk, and B. N. Breizman.
1B5. Fluid/Kinetic Models for Shear Alfven TAE Instabilities in Tokamaks. D. A. Spong, B. A. Carreras, and C. L. Hedrick.

MONDAY AFTERNOON

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

1C1. Neutral Negative Energy Modes for Vlasov-Poisson Equilibria. B. Shadwick and P. J. Morrison.
1C2. Single-Equation DTEM Calculations with Two Nonlinearities. K. L. Sidikman, B. A. Carreras, N. Dominguez, L. Garcia, and P. H. Diamond.
1C3. Similarity Variables and MHD Stability Thresholds. D. Montgomery and X. Shan.
1C4. Electron-Cyclotron Current Drive in the Tokamak Physics Experiment. A. H. Kritz, S. H. Radin, and G. R. Smith.
1C5. Particle-in-Cell Calculations on Massively Parallel Computers. P. M. Lyster, P. C. Liewer, R. D. Ferraro, and V. K. Decyk.
1C6. Possible Poloidal Asymmetry Effects in Beam-Heated TFTR Plasmas. Z. Chang, J. D. Callen, S. D. Scott, and L. C. Johnson.
1C7. Gyrofluid and Kinetic Calculations in Toroidal Geometry. A. Y. Aydemir.
1C8. Radiative Condensation and Boundary Condition Effects in Tokamak Edge Turbulence. L. A. Charlton, B. A. Carreras, J.-N. Leboeuf, and V. E. Lynch.
1C9. Symplectic Kick Maps for Arnold Diffusion and Explosive Instability in Plasmas. C. S. Kueny and P. J. Morrison.
1C10. Dielectric Response and Fluctuations in Gyrokinetic Plasma. J. A. Krommes.
1C11. Turbulent Ion Transport in the General Toroidal Geometry. E. G. Heo, B. H. Park, D.-I. Choi, J. Hernandez, W. Horton, and P. N. Yushmanov.
1C12. Self-Consistent Generation of Sheared Flow and Stabilization of Raleigh-Taylor Convection Cells. J. F. Drake, J. Finn, P. N. Guzdar, A. B. Hassam, and P. H. Diamond.
1C13. Numerical Instability in a 2D Gyrokinetic Code Caused by Divergent ExB Flow. J. A. Byers, A. M. Dimits, and Y. Matsuda.
1C14. Stability of the Low-n TAE Modes. C. Z. Cheng and G. Y. Fu.
1C15. Toroidal and Trapped Ion ITG Modes with Anisotropic eta (sub i). H. Song and A. K. Sen.
1C16. A Model for Dissipative Trapped Electron Mode Turbulence with Ion Landau Damping and Finite Larmor Radius Effects. N. Dominguez, C. L. Hedrick, and J.-N. Leboeuf.
1C17. Edge Plasma Confinement in a Field-Reversed Configuration. L. C. Steinhauer and R. A. Clemente.
1C18. Loss of Passing Energetic Particles due to Low Frequency, Low-n MHD. H. E. Mynick.
1C19. Ballooning Stability Analysis and Optimization of Tokamak Equilibria. J. A. Holmes, D. J. Strickler, and Y.-K. M. Peng.
1C20. Nonlinear Evolution of Internal Kink Modes in the Collisionless and Semi-Collisional Regime. R. D. Sydora, H. Naitou, and J. M. Dawson.
1C21. Graph Massage, an Improved Technique in Moving Finite Elements. A. Kuprat, K. Miller, and A. H. Glasser.
1C22. The Realizable Markovian Closure: A Statistical Approximation for Drift-Wave Turbulence. J. C. Bowman, J. A. Krommes, and M. Ottaviani.
1C23. Toroidal Mode Structure of Long Wavelength Microinstabilities. W. M. Tang and G. Rewoldt.
1C24. Two-Fluid MHD Description of the Internal Kink Mode in Tokamaks. L. Zakharov, B. Rogers, and B. Coppi.
1C25. Simulation of Lower Hybrid Current Profile Modification Experiments. J. Kesner, S. Jones, S. Luckhardt, S. Bernabei, and V. Fuchs.
1C26. Applications of the Quiet Implicit PIC Method. D. C. Barnes and R. A. Nebel.
1C27. Stability Analysis of the Internal 1/1 Mode in Tokamaks and Limitations of the Resistive MHD Model. W. Stodiek, M. H. Hughes, J. Manickam, and J. L. Johnson.
1C28. Saturation of Alpha Particle Driven Alfven Wave Turbulence Through Ion Compton Scattering. F. Y. Gang.
1C29. Solution of Edge Plasma Transport Equations by a Mapping Technique. F. L. Hinton.
1C30. X-point Effects on Particle Orbits and Neoclassical Transport. E. R. Solano and R. D. Hazeltine.
1C31. Anomalous Electron Pinches in Hot Electron Plasmas. R. R. Dominguez.
1C32. Beta-limit Evaluation for the TJ-IU Torsatron. C. Alejaldre, E. Ascasibar, L. Garcia, A. Lopez Fraguas, A. Varias, B. A. Carreras, and N. Dominguez.
1C33. Quasi Three-Dimensional Electron Holes in Magnetized Plasma. D. Jovanovic and W. Horton.
1C34. The Asymptotic Spectrum of a Viscous 2-D Turbulence. M. Wakatani, Y. Z. Zhang, X. N. Su, S. M. Mahajan, and W. Horton.

1C35. A Fully Nonlinear Characteristic Method for Gyrokinetic Simulation. W. W. Lee and S. E. Parker.
1C36. Resonant Pfirsch-Schluter Currents and Equilibrium Magnetic Island Formation. C. C. Hegna, J. D. Callen, and J. N. Talmadge.
1C37. The Direct Interaction Approximation Applied to a Dissipative Drift Wave Turbulence Model. J. A. Crotinger, W. P. Dannevik, and A. E. Koniges.
1C38. Current Drive by Lower Hybrid Waves in Combination with Fast Alfven Waves. A. K. Ram, A. Bers, V. Fuchs, R. W. Harvey, and M. G. McCoy.
1C39. Transport Inferred from Consideration of Particle Orbits in Drift Turbulence. P. M. Bellan.
1C40. Effects of Neutrals on Tokamak Edge Plasma. M. D. Calvin, R. D. Hazeltine, and P. M. Valanju.
1C41. Effects of Flux Surface Jitter on Linear Instabilities. M. G. Prahovic, A. Y. Aydemir, R. D. Hazeltine, and A. Thyagaraja.
1C42. The Kinetic Kink Mode. R. Betti, J. P. Freidberg, and S. Migliuolo.
1C43. Chaotic Transport by Drift/Rossby Waves in Analogous Plasma and Rotating Fluid Systems. D. Del-Castillo-Negrete, P. J. Morrison, W. Holloway, T. Solomon, and H. L. Swinney.
1C44. Effect of Finite Pressure on Tearing Modes. A. Bhattacharjee, R. Iacono, C. Ronchi, J. M. Greene, and M. H. Hughes.
1C45. Alfven Wave Resonance for Finite Length Field Lines. E. Hameiri.
1C46. Forced Reconnection and Current Sheet Formation in Taylor's Model. X. Wang and A. Bhattacharjee.
1C47. Stability of High-n TAE Modes in the Presence of Fusion Alpha Particles. G. Y. Fu and C. Z. Cheng.
1C48. Theoretical Studies of Low Frequency Plasma Heating and Current Drive in Tokamaks. P. E. Moroz, N. Hershkowitz, and J. A. Tataronis.
1C49. The Magnetic Configuration of an Inductively Driven Steady-State Toroidal Plasma. T. K. Chu.
1C50. Dielectric Energy versus Plasma Energy. P. J. Morrison and D. Pfirsch.

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

1D1. The NRL Mode and Phase-Locked Quasioptical Gyroklystron for Fusion Plasma Heating. A. W. Fliflet, R. P. Fischer, and W. M. Manheimer.
1D2. Two-Dimensional Numerical Simulation of Trapped Ion Mode and Drift Wave Turbulence on a Nested kappa-Space Grid. O. T. Kingsbury and R. E. Waltz.
1D3. Theory-Based Transport Simulations of TFTR L-mode Plasmas. G. Bateman and C. E. Singer.
1D4. An Optimum Efficiency Current Drive for Confining a Tokamak Plasma. B. Amini.
1D5. Nonlinear MHD Spectral-Method Computation with Spatially-Variable Resistivity. X. Shan and D. Montgomery.
1D6. Stability of Non-Axisymmetric Configurations of a Non-Neutral Plasma Column. R. A. Smith and T. M. O'Neil.
1D7. Similarity Solutions for RMHD. R. Acevedo and P. J. Morrison.
1D8. Stabilization of External Kinks in Tokamaks. J. Manickam.
1D9. Short-Wavelength Electromagnetic Fluctuations in Edge Plasmas: Nonlinear Features. M. O. Vakulenko and P. P. Sosenko.
1D10. Self-Consistent Theory for Low-Z(sub a) Impurity Pellet Ablation in High Temperature Tokamaks. L. Vahala, G. Gerdin, and P. B. Parks.
1D11. Scaling of ExB Particle Diffusion in Regular and Random Hamiltonians. M. B. Isichenko and W. Horton.
1D12. Potential and Density Distributions in Inertial-Electrostatic Confinement Systems. R. W. Bussard and K. E. King.
1D13. Inertial-Electrostatic Confinement Studies. R. A. Nebel, L. Turner, R. W. Bussard, and G. H. Miley.
1D14. TRANSP Analysis of Supershots with ICRF Heating in TFTR. R. C. Goldfinger, D. B. Batchelor, C. K. Phillips, G. W. Hammett, D. C. McCune, J. R. Wilson, and M. C. Zarnstorff.
1D15. Neoclassical Diffusion in a Turbulent Plasma. P. N. Yushmanov.

1D16. A Unified Theory of Tokamaks and Stellarators. F. Bauer, P. Garabedian, and M. Taylor.
1D17. Computer Simulation of Transport Driven Current in Tokamaks. W. J. Nunan, R. D. Sydora, and J. M. Dawson.
1D18. Energy and Current Transport: Symmetry Breaking and Degradation. F. Pegoraro and B. Coppi.
1D19. The Ballooning Instability in Vortex Rings with Swirl. A. Lifschitz and E. Hameiri.
1D20. Active Control of Fluctuations in a Reversed-Field-Pinch. Y. L. Ho and D. D. Schnack.
1D21. Kinetic Toroidal eta(sub i)-mode Study in the Presence of Parallel Sheared Flow. J. Q. Dong and W. Horton.
1D22. Modification of the Preische Pest Post-Processor. J. L. Johnson and J. Manickam.
1D23. Low-Frequency Plasma Motion: Energy Conservation Law. P. P. Sosenko.
1D24. Turbulent Transport Across a Separatrix due to ETG Driven Instability in Tokamak SOL. X. Q. Xu, P. H. Diamond, and M. N. Rosenbluth.
1D25. Generation of a Minimum Enstrophy Flow in the Tokamak Scrapeoff Layer. N. Mattor and R. H. Cohen.
1D26. A Hybrid Particle-Fluid Simulation for Model Tokamak Plasma Edge Turbulence. C. K. Birdsall and X. Q. Xu.
1D27. Confinement Enhancement in Multiple-Mirror Systems by Transient Potential Barriers. R. F. Post.
1D28. Energy Cascades for Drift Turbulence with Trapped Ions. S. Rath and J. A. Krommes.
1D29. Model Studies of L-H Transition Dynamics with Turbulently Generated Differentially Rotating Flow. P. W. Terry, P. H. Diamond, B. A. Carreras, and K. L. Sidikman.
1D30. The Exact and Drift Hamiltonian. Q. Yao and A. H. Boozer.
1D31. Bootstrap Currents in Tokamaks of Arbitrary Aspect Ratio. H. R. Wilson.
1D32. Three-Dimensional Fluid Simulation of Edge Turbulence in Tokamks. P. N. Guzdar, J. F. Drake, D. R. McCarthy, A. B. Hassam, and C. S. Liu.
1D33. Bohr-Sommerfeld Eigenfrequencies and Eigenfunctions for Vector Wave Equations. R. G. Littlejohn and W. G. Flynn.
1D34. Two Dimensional Aspects of Toroidal Drift Waves in the Ballooning Representations. X. D. Zhang, Y. Z. Zhang, and S. M. Mahajan.
1D35. Approximate Model of DTEM with Ion Landau Damping and FLR Effects. C. L. Hedrick, J.-N. Leboeuf, and N. Dominguez.
1D36. Reduced Microscopic Description of Magnetized Plasma. V. K. Decyk and P. P. Sosenko.
1D37. Filamentary Construct of High-Beta Plasmas. T. Tajima, R. Kinney, and N. Petviashvili.
1D38. Painleve Analysis of Particle Dynamics in Magnetic and Electric Fields Associated with Reconnection. J. W. Larson and E. R. Tracy.
1D39. Poloidal Rotation and Density Asymmetries in a Tokamak Plasma with Strong Toroidal Rotation. W. M. Stacey, Jr..
1D40. Gyro-Landau Fluid Model Simulations of Ion Temperature Gradient Mode Turbulence in Toroidal Geometry. R. E. Waltz, G. D. Kerbel, and G. W. Hammett.
1D41. Fast Ion Driven Bernstein Instabilities via Relativistic Mass Variation. K.-R. Chen.
1D42. Calculations of Combined LH, FW, and EC Power Deposition and Current Drive. R. W. Harvey and M. G. McCoy.
1D43. 1D and 2D Code-Merging with Applications to a Self-Consistent Core-Edge Plasma Simulation. A. Tarditi.
1D44. Far Field ICRF Sheath Formation on Walls and Limiters. J. R. Myra and D. A. D'Ippolito.
1D45. Magnetofluid Dynamics with Electron Pressure and Inertia. C. E. Seyler.
1D46. Lower Hybrid Calculations for PBX-M. D. W. Ignat, E. J. Valeo, S. C. Jardin, and S. Bernabel.
1D47. Two-Dimensional Detailed MHD Simulation of Deuterium-Fiber-Initiated Z-Pinches. P. T. Sheehey, I. R. Lindemuth, R. H. Lovberg, and R. A. Riley, Jr..
1D48. Tokamak Transport Based on the Thirteen Moments Model. M. K. Tippett.
1D49. Stationary 3D Vlasov Plasma Equilibria with FLR Effects. D. R. Martin and D. V. Anderson.
1D50. Operational Scenarios for a Steady-State Advanced Tokamak (SSAT). W. M. Nevins and Team. TPX.

TUESDAY MORNING

2A Review Talk
8:30am - 9:20am
Presiding: W. M. Nevins

2A1. New Mathematical Methods for Linear Plasma Problems. A. N. Kaufman.

2B ORAL SESSION
9:30am - 12:00pm
Presiding: G. Morales

2B1. The Interaction of Energetic Alpha-Particles with Intense Lower Hybrid Waves. N. J. Fisch and J.-M. Rax.
2B2. Energetic Alpha Particle Induced Bootstrap Current. C. T. Hsu, D. J. Sigmar, and K. C. Shaing.
2B3. On the Possibility of a Steady State Tokamak Maintained by Bootstrap Current Drive Alone. J. M. Dawson, W. J. Nunan, and S. Ma.
2B4. Electron-Temperature-Gradient Turbulence in Tokamak Scrape-Off Layers. R. H. Cohen, H. L. Berk, D. D. Ryutov, Yu. Tsidulko, and X. Q. Xu.
2B5. Physics Principles of Ignition Experiments. B. Coppi, M. Nassi, and L. E. Sugiyama.

TUESDAY EVENING

2C POSTER SESSION
8:00pm - 10:00pm

2C1. Application of Plasma Theory Techniques to Fusion Engineering Problems: A Fast Solver for the Time Evolution of the PF Currents. J. Wei, J. P. Freidberg, and S. W. Haney.
2C2. Net Transport Across Fluctuating Flux Surfaces. J. B. Hollenberg and J. D. Callen.
2C3. Application of Plasma Theory Techniques to Fusion Engineering Problems: Quench Protection in Superconductors. A. Shajii and J. P. Freidberg.
2C4. Low Beta Ideal MHD Stability of DIII-D Revisited: Wall Stabilization. A. D. Turnbull.
2C5. Kinetic Description of Toroidal Alfven Eigenmodes. W. Q. Li, S. M. Mahajan, D. W. Ross, and M. S. Chu.
2C6. Effects of Sheared Toroidal Rotation on Single Particle Dynamics, Nonlinear Gyrokinetics, and Wave-Particle Interaction. T. S. Hahm.
2C7. Transport in a Stochastic Magnetic Field. R. B. White, J.-M. Rax, and Y. Wu.
2C8. MHD Tilt Stability of Non-Stationary Spheromaks. U. Shumlak, J. L. Eddleman, T. K. Fowler, J. H. Hammer, and E. C. Morse.
2C9. Specific Transport Process under ECRH in Tokamaks. V. I. Poznyak and P. N. Yushmanov.
2C10. Transport Simulation of Oscillating Gas-Puff on TEXT using Theoretical Models. D. W. Ross, B. Richards, W. L. Rowan, and J. C. Wiley.
2C11. Magnetic Reconnection in Electron-Magnetohydrodynamics. S. V. Bulanov, F. Pegoraro, and A. S. Sakharov.
2C12. Perpendicular Ion Acceleration at Frequencies Larger than the Ion-Cyclotron Frequency. K. Reitzel, G. J. Morales, and V. K. Decyk.
2C13. ELMS as a Kelvin-Helmholtz Instability. H. R. Strauss.

2C14. The Performance of a Fluid Code on Massively Parallel Machines. V. E. Lynch, B. A. Carreras, J. B. Drake, J.-N. Leboeuf, P. Liewer, and D. W. Walker.
2C15. Gyrokinetic Particle Simulation of Impurity Transport. R. A. Santoro and W. W. Lee.
2C16. Reconnection Driven by Electron Pressure and the Fast Sawtooth Crash. R. G. Kleva, J. F. Drake, and F. L. Waelbroeck.
2C17. Monte-Carlo Simulation of Kinetic Transport Near the Tokamak Edge. H. Xiao, H. Ye, Y. Z. Zhang, and R. D. Hazeltine.
2C18. Stochastic Broadening in a Single-null Divertor Tokamak. A. Punjabi, A. Verma, and A. H. Boozer.
2C19. Non-Standard High Energy Ion Orbits: Slowing Down and MHD Stabilization. L.-G. Eriksson, H. L. Berk, F. Porcelli, and R. Stankiewicz.
2C20. Bootstrap Current Driven by Energetic Ion Species in Tokamaks. C. S. Chang.
2C21. ICRF Fast Wave Current Drive and MHD Equilibrium Model. P. T. Bonoli, R. C. Englade, M. Porkolab, and M. E. Fenstermacher.
2C22. Profiles Marginally Accessible to the Second Region of Stability. M. S. Chance.
2C23. Further Studies of Flow Effects on Long Wavelength Drift Wave Turbulence. Y.-M. Liang and P. H. Diamond.
2C24. Predictions of Alpha Parameters in Tokamaks with Q (sub DT) = 5. R. V. Budny, D. C. McCune, and S. J. Zweben.
2C25. The Implications of the Generalized Kirchhoff's Law on ECE Emission Diagnostics and the Role of Synchrotron Radiation in Power Balance and Trans. D. G. Swanson and V. F. Shvets.
2C26. Two-Dimensional Edge Plasma Modeling (Newedge). C. Koesoemodiprodjo, A. K. Prinja, and D. A. Knoll.
2C27. Nonadiabaticity and Toroidal Mode Coupling in Collisional Drift Waves. M. Schluter and B. Scott.
2C28. The Temperature Dependence of LHCD Efficiency. K. Kupfer and D. Moreau.
2C29. Ponderomotive Current Drive by Alfven-Ion Cyclotron Waves. C. Litwin and N. Hershkowitz.
2C30. Physics Basis for Advanced Tokamaks. S. C. Jardin, C. Kessel, J. Manickam, D. A. Monticello, and N. Pomphrey.
2C31. Effect of Magnetic Fluctuations on the Lower Hybrid Wave Propagation in Tokamaks. G. Vahala, L. Vahala, and P. T. Bonoli.
2C32. MDI: Mathematica Database Interface for the MFE Database. J. C. Wiley and W. H. Miner, Jr..
2C33. Rapid Quenching of Collisional Drift Wave Turbulence by E cross B Velocity and Vorticity Gradients. B. Scott.
2C34. Nonlinear Evolution of Alpha Particle Driven Alfven Turbulence and Anomalous Alpha Transport. D. J. Sigmar and F. Y. Gang.
2C35. Empirical Spectral Codes for Tokamak Turbulence. G. R. Smith, R. H. Cohen, E. D. Boerner, and A. M. Dimits.
2C36. A Normal Form Theory of Pairwise Linear Mode Conversion. W. G. Flynn and R. G. Littlejohn.
2C37. Electromagnetic Effects in Convective Cell Fluctuations and Diffusion. O. H. Sitenko and P. P. Sosenko.
2C38. Computational Study of the Interplay of ExB and Polarization Drift Nonlinearities in Drift Wave Turbulence. D. E. Newman, P. W. Terry, and P. H. Diamond.
2C39. Effect of Bootstrap Current Modified Profiles on Ideal MHD Stability Limits for Long Pulse, High Poloidal Beta Equilibria in TFTR. S. A. Sabbagh, M. E. Mauel, G. A. Navratil, M. G. Bell, R. V. Budny, C. E. Bush, E. D. Fredrickson, J. Manickam, D. C. McCune, K. M. McGuire, H. K. Park, E. J. Synakowski, G. Taylor, R. M. Wieland, M. C. Zarnstorff, J. Kesner, and M. W. Phillips.
2C40. Edge Turbulence Scaling with Shear Flow. Y. Z. Zhang and S. M. Mahajan.
2C41. Stability Theory Formulated in Terms of a Scalar Representation. E. K. Maschke.
2C42. Mathematica Approach to Neoclassical Theory. Y.-B. Kim.
2C43. Magnetic Topology Transitions in Collisionless Plasmas. P. Detragiache and B. Coppi.
2C44. High Beta Axisymmetric D-(3)He Reactor with Internal Levitated Coil. V. P. Pastukhov, A. I. Morozov, and A. Yu. Sokolov.
2C45. MHD Computation of Effects of Feedback and Mode Rotation on RFP Tearing Modes. E. J. Zita, S. C. Prager, and Y. L. Ho.

2C46. Bootstrap Dependence on Profile Parameters and J(sub bs) Alignment. N. Pomphrey.
2C47. Vortex-Wave Dynamics in an Inhomogeneous Magnetized Plasma. M. Kono, I. Shibahara, and W. Horton.
2C48. Kinetic Theory of Toroidicity-Induced Alfven Eigenmodes. R. R. Mett and S. M. Mahajan.
2C49. Generation of Toroidal Convective Cells in the Tokamak Edge. D. R. McCarthy, P. N. Guzdar, J. F. Drake, and A. B. Hassam.
2C50. Impurity Effects on Toroidal ITG Modes Circular vs. Elliptical Plasma Crossections. S. Migliuolo.

WEDNESDAY MORNING

3B ORAL SESSION
8:30am - 10:30am
Presiding: E. Tracy

3B1. Anomalous Kinetics of Incomplete Chaos. G. M. Zaslavsky.
3B2. Nonlinear Drift Wave Structures in a Sheared Magnetic Field. X. N. Su, W. Horton, and P. J. Morrison.
3B3. Nonlinear Skin Phenomena in (Almost) Collisionless Short-Duration Plasmas. A. Fruchtman and L. I. Rudakov.
3B4. The Theory of Nearly Incompressible Magnetofluid-Dynamics. G. P. Zank and W. H. Matthaeus.

3C POSTER SESSION
10:30am - 12:30pm

3C1. The Effects of Finite-Beta and of Radial Boundary Conditions in Gyrofluid Equations. G. W. Hammett, W. Dorland, and M. A. Beer.
3C2. Nonlinear Gyrofluid Simulation and Analysis: ITG Turbulence. W. Dorland, G. W. Hammett, and T. S. Hahm.
3C3. Tokamak Scrape-Off Layer Simulations Using the Fully Implicit LEDGE Code. T. D. Rognlien, J. L. Milovich, M. E. Rensink, R. H. Cohen, and T. B. Kaiser.
3C4. Influence of Various Physics Phenomena on Fast-Wave Current Drive Efficiency in Advanced Tokamaks. E. F. Jaeger, D. B. Batchelor, M. D. Carter, R. C. Goldfinger, and D. C. Stallings.
3C5. Finite-Beta Gyrokinetic Plasma Simulation using the Canonical Momentum Formulation. J. C. Cummings and W. W. Lee.
3C6. Ion Cyclotron Heating with Lower Hybrid Waves. E. C. Morse and G. J. DiPeso.
3C7. Nonadiabatic Interaction of Low-Energy Particles with Large-Amplitude Electron-Cyclotron Waves. G. V. Stupakov and R. H. Cohen.
3C8. Gyrokinetic Simulations of Ion-Temperature-Gradient Modes with Sheared Poloidal Velocity. B. I. Cohen, A. M. Dimits, T. J. Williams, and N. Mattor.
3C9. Analytic Derivation of the Magnetosonic Wave Reflection Field for ICRF Heating in Tokamak Geometry. D. R. Cook, A. N. Kaufman, A. J. Brizard, and H. Ye.
3C10. RF Active Confinement Control of Edge Turbulence: High Frequency Waves and Helicity Injection. G. G. Craddock, P. H. Diamond, H. Biglari, and M. Ono.
3C11. Collisionless Heating in the FRC from a Chaotic Conductivity. W. Horton, M. B. Isichenko, J. Y. Kim, and T. Tajima.
3C12. Numerical Three Dimensional Equilibria with Pressure Anisotropy. S. P. Hirshman, W. A. Cooper, S. Merazzi, and R. Gruber.
3C13. Symbolic Signal Processing and Pattern Recognition. A. B. Rechester and R. B. White.
3C14. Poloidal Beta Scaling for a Bootstrapped Tokamak. R. Iacono and A. Bhattacharjee.
3C15. Asymptotic Enstrophy Spectrum of 2-D Turbulence with Velocity Shear. S. M. Mahajan and Y. Z. Zhang.
3C16. Parallelizing Algorithms for Non-Linear Gyrofluid Turbulence Computations. G. D. Kerbel and R. E. Waltz.

3C17. Exact Analytical Solution of the Toroidal Singular Mode Equations. A. H. Glasser.
3C18. Transport Processes in the Reversed-Field Pinch. D. D. Schnack and Y. L. Ho.
3C19. Nonlinear Evolution of Resistive Tearing Mode Instability with Shear Flow and Viscosity. L. Ofman, P. J. Morrison, and R. S. Steinolfson.
3C20. Gyrokinetic Simulations of Unstable Toroidal eta(sub i) Modes. H. V. Wong.
3C21. Resonant Damping of Toroidal Alfven Eigenmodes in General Equilibria. F. Zonca and L. Chen.
3C22. Nonlinear Poloidal Density Variation in H-Mode Plasmas. K. C. Shaing, R. D. Hazeltine, S. Attenberger, S. P. Hirshman, and W. A. Houlberg.
3C23. Nonlinear Island Dynamics. T. J. Schep, F. Pegoraro, and J. Rem.
3C24. A New Mechanism of Thermonuclear Reaction. H.-Z. Wang.
3C25. Using LEX and YACC to Build a Parser for the MFEDB. R. T. McCann, W. H. Miner, Jr., and J. C. Wiley.
3C26. Stability and Neoclassical Effects in High Beta Tokamaks. S. Cowley.
3C27. Onsager Symmetry of Transport in Toroidal Plasmas. A. H. Boozer.
3C28. Lyapunov Stability of Toroidal Axisymmetric MHD Equilibria. J. J. E. Herrera, J. A. Almaguer, and J. J. Martinell.
3C29. A Three Dimensional, Toroidal Two Fluid Model with Hot Particles. L. E. Sugiyama and W. Park.
3C30. Phase-Space Formulations for the Vlasov-Fluid and Kinetic-MHD Models. A. J. Brizard.
3C31. Application of the PIES Code to Configurations with Large Magnetic Islands. A. Salas, A. Lopez Fraguas, A. H. Reiman, D. A. Monticello, and J. L. Johnson.
3C32. Onset of the Sawtooth Crash. F. L. Waelbroeck.
3C33. Quasilinear Diffusion of Photons in an ISI Beam. A. J. Neil and E. R. Tracy.
3C34. Electrostatic Helical Vortices. H. Chen and D. Montgomery.
3C35. Advanced Tokamaks in the Second Stability Regime. J. J. Ramos.
3C36. The Isotopic Effect and Impurity Drift Modes. B. Coppi and S. Migliuolo.
3C37. Linear Stability Thresholds of Alpha Particle Driven High-n Toroidal Alfven Eigenmodes. H. L. Berk, D. M. Lindberg, J. W. Van Dam, H. Ye, B. N. Breizman, and M. N. Rosenbluth.
3C38. Non-Ideal Analysis of Toroidal Alfven Eigenmodes. M. N. Rosenbluth, J. Candy, H. L. Berk, J. W. Van Dam, and D. M. Lindberg.
3C39. Alfven Continuum Damping of Global MHD Modes. M. S. Chu, J. M. Greene, A. D. Turnbull, H. L. Berk, and M. N. Rosenbluth.
3C40. Dynamics of Fluid Models for Collisional and Collisionless Drift-Wave Turbulence. A. E. Koniges, G. G. Craddock, J. A. Crotinger, and P. H. Diamond.
3C41. Efficient Higher-Order Symplectic Integration Algorithms. J. R. Cary.
3C42. ICRF-Driven Convection in Tokamaks. D. A. D'Ippolito, J. R. Myra, J. Jacquinot, and M. Bures.
3C43. Toroidal Effects on Drift Wave Turbulence. M. Gray, M. J. LeBrun, T. Tajima, G. Furnish, Y. Kishimoto, and W. Horton.
3C44. Approximation to MHD in the Low Resistivity Limit. A. A. Blank and M. E. Kress.
3C45. Gyrokinetic Delta f Simulation in a Toroidal Metric. M. J. LeBrun and T. Tajima.
3C46. Energy Confinement Scaling in the ATF Torsatron. R. A. Dory and M. Murakami.
3C47. Low-Frequency Fluctuations in Plasma Magnetic Fields. S. Cable, T. Tajima, and R. M. Kulsrud.
3C48. Magnetic Surfaces in a Steady-State Tokamak. R. Kinney, T. Tajima, and H. Irie.
3C49. Investigation of Possibility of LH/FW Synergism. S. C. Chiu and Y. R. Lin-Liu.
3C50. A New Modeling of Anomalous Ion Thermal Transport by the Toroidal Ion Temperature Gradient Mode. J. Y. Kim, W. Horton, and B. Coppi.

1992 International Sherwood Fusion Theory Conference
April 6-8, 1992, Santa Fe, New Mexico

THE CONTROLLED RELEASE OF FUSION ENERGY USING THE DEUTERIUM TRITIUM REACTION IN JET

The work of the JET Team – presented by Dr. A. Gibson

JET
United Kingdom

The development of high performance deuterium discharges in JET opened up the possibility of carrying out a limited series of experiments using deuterium-tritium mixtures.

The colloquium will describe these experiments and the results obtained. The future programme of JET and its place in European Fusion development will be briefly outlined.

Abstract for 1992 Sherwood Theory Meeting

RESISTIVE INTERNAL KINKS AND ICRF PHASING CURRENT DRIVE

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For q-profiles where q on axis is allowed to drop significantly below unity, the theoretical threshold for the onset of resistive internal kink modes[1] depends importantly on the internal inductance within the $q = 1$ surface[2], on the plasma bulk[2] and fast particle pressure gradients[3] within the $q = 1$ surface, and on the local magnetic shear at $q = 1$[4]. Resistive internal kinks are believed to be responsible for the internal plasma (sawtooth) relaxations in tokamaks.

All these theoretical ingredients play a role in the interpretation of very recent JET experiments[5] where the sawtooth period has been dramatically influenced by the injection of phased Ion-Cyclotron-Radio-Frequency waves. Phasing the ICRF antennas implies that waves are travelling along the toroidal direction. This raises the possibility of minority ion current drive, according to an early suggestion by Fisch[6]. Differences in the sawtooth behaviour when the RF resonance is placed near $q = 1$ on the high field vs low field sides can be understood in terms of particle trapping and collisional effects..

The emerging theoretical picture is the following. As shown, e.g., in Ref. 3, the conservation of magnetic flux through the fast ion precessional drift orbits (third adiabatic invariant) can lead to sawtooth stabilisation, provided the fast particle pressure is well peaked within the $q = 1$ surface, as is the case with on-axis ICRF heating. With off-axis ICRF phasing the modification of the magnetic shear near $q = 1$ may play the most important role. Simulations of the sawtooth ramps show that, consistently with the experimental observations, positive phasing on the high field side leads to a reduction of the local shear, hence to a lengthening of the sawtooth period up to 1-2secs, provided the thermal plasma poloidal beta within $q = 1$ is sufficiently low. Negative phasing has the opposite effect of shortening the sawtooth period.

In conclusion, ICRF phasing provides a new experimental option which is relevant for both the under-standing and the control of sawteeth.

1 B. Coppi et al., Fiz. Plasmy 6, 961 (1976).
2 M.N. Bussac et al., Phys. Rev. Lett. 35, 1638 (1975).
3 F. Porcelli, Plasma Phys. and Contr. Fusion 33, 1601 (1991), and references therein.
4 S. Migliuolo et al., Phys. Fluids B3, 1338 (1991).
5 D.F.H. Start et al., IAEA Tech. Workshop, Arles, 1991; J. Jacquinot et al., APS invited paper, submitted to Phys. Fluids.
6 N.J. Fisch, Nucl. Fusion 21, 15 (1981).

⟹Sherwood Conference April 1992⟸

3D Toroidal Gyrokinetic Simulation of Ion Temperature Gradient Driven Turbulence[1]

S. E. Parker and W. W. Lee

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We have developed a three dimensional electrostatic toroidal gyrokinetic simulation to study tokamak turbulence and transport. Our investigation of the ion temperature gradient driven instability and the associated nonlinear behavior is presented. The ion gyrokinetic equation is evolved using either a linear, partially linear, or fully nonlinear weighting scheme[2] (more commonly called δf methods) and the electrons are treated as adiabatic. This permits a considerable reduction in the number of particles needed for resolution. Slab like coordinates are used which are convenient for Fourier decomposition of the gyrokinetic field equation. In terms of the usual toroidal coordinates (r, θ, ψ) they are: ($x = r\cos\theta, y = r\sin\theta, z = -(R_0 - a)\psi$). Currently, the the code is running on a massively parallel computer(CM2) which allows simulations of relatively large systems (e.g. a 48 ρ_i minor radius). This permits resolution of higher poloidal and toroidal harmonics (e.g. $m \lesssim 16$, and $n \lesssim 8$). Typical runs up to this point have been using 64x64x64 grid cells, one particle per grid cell, with run times taking 1-2 hours on one quarter(16k processors) of a fully configured CM2. In terms of state of the art computing these runs are modest in size. In the initial phase of the run, we observe a clean linear growth of the most unstable toroidal harmonic and the associated 2D eigenmode in (r, θ) with a ballooning type structure where $k_r \ll k_\theta$. In the steady-state, both long and short perpendicular wavelengths are enhanced and $k_r \simeq k_\theta$. Broad scale (i.e. many modes are present) turbulence with fluctuation levels of $e|\phi_k|/T \lesssim 1\%$ are observed. The steady-state heat flux is higher than that of sheared slab runs with comparable parameters. Results of the η_i mode simulation will be presented showing the nonlinear evolution of potential, density, and heat flux. In the future, we plan to add drift kinetic electrons and finite beta effects ($\delta\mathbf{B}_\perp$) to the toroidal code greatly extending it's applicability.

[1]Work supported by the DOE Fusion Postdoc Program and DOE Contract No. DE-AC02-76-CHO-3073.

[2]W.W. Lee and S.E. Parker, this conference.

Nonlinear Particle and Fluid Simulations using Quasi-Ballooning Coordinates[1]

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Many instabilities of interest in tokamak plasmas, for example ion temperature gradient driven (ITG) modes, trapped-electron modes, and pressure-driven MHD modes have a mode structure which is highly elongated in the direction of the magnetic field. Efficient use of grid resolution in simulations of turbulence with such a structure requires that one of the coordinate directions be at least approximately aligned with the magnetic field. The main difficulty that arises is in the implementation of the resulting periodicity conditions. Numerical methods have been developed that address this difficulty by letting grid lines that exit one boundary in the transformed toroidal-poloidal plane continue exactly into (generally different) grid lines when they reenter at the opposite boundary.[2] This choice permits the coordinate and magnetic field directions to be aligned closely enough (but not exactly — hence the name "quasi-ballooning coordinates") to allow essentially optimal use of the grid resolution, even for general profiles of the magnetic rotational transform. These coordinates have been implemented in a three-dimensional finite-difference nonlinear fluid code. Preliminary investigations show a striking result: the transport due to ITG-driven turbulence in the fluid limit does not depend strongly on the magnetic shear. In contrast, simulations of the same system using standard toroidal-poloidal grids (or grids that are field-aligned only at one radial surface but do not twist with the magnetic field) display a much stronger fake dependence on the magnetic shear due to the decrease in the effective perpendicular resolution as the shear length decreases. Complete results of this investigation will be presented. Work to implement quasi-ballooning coordinates in a partially-linearized ("δf") gyrokinetic particle code is near completion on the Cray-2 and is underway on the CM-2. Results from simulations of ITG-driven turbulence using the Cray-2 code will be presented. The new issues that arise in the implementation and optimization of the code on the CM-2 will be discussed and performance results will be given.

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[1]Performed by LLNL for USDoE under contract W-7405-ENG-48.

[2]A.M. Dimits, in the proceedings of the *14th. International Conference on the Numerical Simulation of Plasmas*, (1991, SAIC - NRL - ONR, Annapolis, MD, paper PWA5).

Map Model for Nonlinear Alpha Particle Interaction with Toroidal Alfven Eigenmodes

*H. Ye, H. L. Berk, and B. N. Breizman**

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The University of Texas at Austin

Instabilities driven by alpha particles in an ignited plasma are a major concern as they can lead to unacceptable anomalous transport resulting from the excitation of Alfven waves, particularly the toroidicity-induced Alfven eigenmode (TAE) [1-4]. We have developed a model to analyze both linear and nonlinear interactions of alpha particles with the TAE mode, taking into account that the characteristic alpha particle orbit's excursion from the flux tube can be comparable or exceed the scale size of the TAE mode structure (in fact for realistic parameters the alpha particle excursion is larger than the relevant structure of the TAE mode). Our work specifically addresses the following questions: (1) what is the magnitude of linear alpha particle "universal" instability drive; (2) how do TAE modes affect nonlinear alpha particle transport.

By taking into account finite orbit excursion, linear theory [5] gives a general expression for the TAE growth rate which includes, as a particular case, the previous result obtained for small orbit excursions. In the limit of large excursions the growth rate is independent on n number rather than being proportional to n as the theory for small excursions would predict. The theory quantifies the magnitudes of the side band resonances $V_{//} = V_A/(2l-1)$ for integer l ($V_{//}$ the alpha particle parallel velocity, and V_A the Alfven speed). These resonances are particularly important in the large orbit limit; specifically they facilitate stochastization of particle orbits.

To analyze nonlinear effects of the wave-particle interaction and to describe stochastic losses of alpha particles, a symplectic map is constructed by calculating analytically the particle displacement after each poloidal transit. With the map a particle's nonlinear dynamics can then be followed over many transits. We also incorporate drag and pitch angle scattering into the map.

By analyzing the principal resonances of the map we can calculate the threshold mode amplitude for the onset of global stochasticity of alpha particle orbits, which gives a qualitative interpretation of the results obtained previously from direct numerical simulations [2]. This map is being developed to self-consistently follow the nonlinear mode saturation due to the change in the distribution of alpha particles. The alpha particle distribution will relax in either a stochastic or nonstochastic manner, in accordance with correct nonlinear orbit dynamics with the self-consistent wave spectrum.

[1] C. Z. Cheng and M. S. Chance, Phys. Fluids **29**, 3695 (1986).
[2] D. J. Sigmar, C. T. Hsu, R. White, and C. Z. Cheng, to appear in Phys. Fluids B, (1992).
[3] K. L. Wong, Phys. Rev. Lett. **66**, 1874 (1991)
[4] W. W. Heidbrink et al., Nucl. Fusion **31**, 1635 (1991).
[5] H. L. Berk, B. N. Breizman, and H. Ye, to appear in Phys. Lett. A , (1992).

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Fluid/Kinetic Models for Shear Alfvén TAE Instabilities in Tokamaks*

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It has recently become possible to include both Landau resonance effects and high order finite Larmor radius corrections within a fully electromagnetic set of fluid moment equations. This offers a new approach for analyzing the effects of fast particles (e.g., neutral beams, alpha populations, ICRF tails, etc.) on tokamak stability which are one of the major remaining areas of physics uncertainty for future toroidal magnetic fusion devices.

As an example of this method, we demonstrate its numerical application to the toroidal Alfvén eigenmode (TAE) instability as excited by a super-Alfvénic hot particle component. The usual reduced MHD poloidal flux and vorticity equations coupled with density and parallel velocity evolution equations for the energetic species are solved using a 3-D toroidal initial value code. We first compare linear growth rates with analytical estimates over a range of parameters and find generally good agreement. The numerical model also shows evidence of damping through coupling with adjacent shear Alfvén continua as appropriate q(r) or $v_A(r)$ profiles are chosen; the damping rates compare reasonably with recent theories for continuum damping of the TAE. In addition, we will discuss further components required for a comprehensive model of the TAE such as: electron and ion Landau damping (determines the β_{hot} threshold), ion FLR (fully discretizes the spectrum), and background plasma pressure gradient drive (couples the TAE strongly with the continuum).

Finally, this model has been extended to the nonlinear regime. Saturated states for the TAE are achieved through quasilinear alpha density profile modification and formation of magnetic island structures which locally flatten the q-profile. The nonlinear dynamics show a delicate interplay between the hot species Landau growth and damping effects, as evidenced by a graphical analysis of the mode structure rotation characteristics. In conclusion, gyrofluid models with Landau closure can include many of the physical mechanisms needed for analyses of energetic particle effects on tokamak stability and are likely to become useful paradigms for understanding such instabilities.

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Neutral Negative Energy Modes for Vlasov-Poisson Equilibria*

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Linear neutral (undamped) modes about Vlasov-Poisson equilibria are investigated. For Penrose stable equilibria with extremal points, it is shown that non-Landau damped neutral modes with phase velocities at minima or maxima of the distribution function do not exist. However, it is also shown that neutral modes can exist with phase velocities of points where both the first and second derivatives of the equilibrium distribution function vanishes. A general energy expression for these kinds of neutral modes is obtained, and compared with other well-known expressions. It is shown in examples that the energy can sometimes be negative. Speculations about nonlinear instability arising form resonance between positive and negative energy modes of this type are made.

*Work is supported by U.S. DoE.

SINGLE–EQUATION DTEM CALCULATIONS WITH TWO NONLINEARITIES*

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Numerical calculations using a single equation model of the dissipative trapped electron mode are being performed. This model contains two nonlinear terms: vorticity advection (the standard drift wave "polarization" nonlinearity) and advection of the density by the $\mathbf{E}\times\mathbf{B}$ velocity arising from trapped–electron modification of the potential (the $\mathbf{E}\times\mathbf{B}$ nonlinearity). Earlier work focused on calculating the characteristics of the turbulence generated by the $\mathbf{E}\times\mathbf{B}$ nonlinearity, which dominates the nonlinear evolution for long wavelengths. The object of the present work is to study the evolution of the turbulence when the effects of the polarization nonlinearity, which dominates for shorter wavelengths, are added.

As a start, single–helicity calculations in sheared–slab geometry are under way. General characteristics of the turbulence generated by both nonlinearities together (fluctuation levels, saturation, and the distribution of energy among modes) will be investigated.

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

**Supported by an appointment to the U.S. DOE Fusion Energy Postdoctoral Research Program administered at Oak Ridge Associated Universities.

SIMILARITY VARIABLES AND MHD STABILITY THRESHOLDS

D. Montgomery and X. Shan, Dartmouth, Hanover, NH, 03755-3528

Abstract

The stability of hydrodynamic shear flows is often determined, for a given geometry, only by the Reynolds number. The question arises as to whether resistive MHD equilibria permit their stability thresholds to be characterized in a similarly economical way. The answer appears to be Yes, if the equilibria are restricted to be axisymmetric, have zero flow, and to be steady states in a periodic straight cylinder with homogeneous boundary conditions. Assuming that the unstable eigenvalues always first appear at zero frequency, it is possible to write the threshold linear eigenvalue equations in a set of dimensionless variables. The only parameters in the dimensionless linear system that depend on anything but the shapes of the assumed resistivity and viscosity profiles (as functions of radius) are the Hartmann number H and the pinch ratio Θ_0. (The pinch ratio may also be expressed as the reciprocal of the aspect ratio times the safety factor at the wall.) Thus for any given shape of the resitivity profile and viscosity profile, a stability boundary can be defined by a curve in the (H, Θ_0) plane. The result is not a short-cut that bypasses the labor of calculating the stability threshold for given profile shapes. But it does say that once the profile shapes are fixed, whether the equilibrium is stable or not is determined by only two numbers. The result generalizes that of Shan et al [1] for the case of uniform resistivity and viscosity, perhaps the only completely soluble case by exact methods.

In the case of recent JET parameter sets for which MHD activity sets in, the pinch ratio is known but estimating the Hartmann number requires an assumption about viscosity. If the usual shear viscosity from Braginskii is used, the threshold Hartmann number is six or seven orders of magnitude larger than it is if one uses the "ion parallel viscosity." Using the ion parallel viscosity leads to a threshold Hartmann number of only about 1320. If MHD equations share qualitative behavior with Navier-Stokes (which they contain as a special case), the order of magnitude agreement would be comfortably close to critical Reynolds number values for shear flows. This suggests (but of course does not prove) that the ion parallel viscosity is what should be used [2].

[1] X. Shan et al, Phys Rev. A, 44, 6800(1991). See figs. 8a,b.
[2] D.Montgomery, JET preprint JET-P(91)64, to appear in Plasma Phys. & Contr. Fusion, 1992; and J. Geophys. Res. 1992 (in press)

Electron-Cyclotron Current Drive in the Tokamak Physics Experiment

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We explore scenarios for injection of electron-cyclotron heating (ECH) power into the Tokamak Physics Experiment (TPX). The purpose of the injected power is to drive current locally near the $q = 2$ surface in order to suppress tearing modes and thereby control disruptions. Effects of finite beam width and divergence are included, as are the effects of scattering of the ECH power by drift-wave turbulence. We consider fundamental O-mode power injected from the low-magnetic-field side of the plasma, with the center of the microwave beam in the plane containing the magnetic axis. Ranges of injection angles and gyrotron frequencies are used to find optimum launch scenarios for two cases: (1) absorption at $q = 2$ near the antenna using power at about 80 GHz, and (2) absorption at $q = 2$ on the far side of the plasma using power at about 120 GHz. Case (1) has the advantage that scattering effects are negligible at any conceivable turbulence level, while case (2) has the advantage that degradation of current-drive efficiency by trapped electrons is absent. Estimates are given of the power required to suppress tearing modes for each case.

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

Abstract for 1992 Sherwood Theory Meeting

Particle-in-Cell Calculations on Massively Parallel Computers

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We are developing a variety of particle-in-cell (PIC) plasma simulation models which will make use of present and future generations of massively parallel computers. One focus is the generalization to three dimensions of the general concurrent particle in cell (GCPIC) algorithm[1]. We are developing a parallel particle decomposition that will work in one, two, or three dimensions as well as allowing flexible choice of domains into cubes, slabs, or elongated rods. The knowledge we learn from this is expected to be used to find efficient decompositions for particle-in-cell codes that will be used for the Numerical Tokamak. The present work is an extension of the method used for a two dimensional electromagnetic GCPIC algorithm that runs on the Intel Touchstone Delta machine at Caltech; this is a MIMD parallel computer with 512 nodes and about 100 times the power of a single processor Cray. We are also porting a simple GCPIC code to a CM2 to test whether the GCPIC algorithm will also run efficiently on a SIMD parallel computer.

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POSSIBLE POLOIDAL ASYMMETRY EFFECTS IN BEAM-HEATED TFTR PLASMAS*

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ABSTRACT

In tokamak plasmas the variations of plasma quantities on a magnetic flux surface and their effects on the plasma are usually expected to be small (*e.g.*, small effect on the already negligible neoclassical perpendicular transport), except possibly near the plasma edge where asymmetric sources can be important and for rapidly rotating plasmas. However, in high beam power TFTR shots the anisotropic fast ion component can be quite large and this could induce some poloidal asymmetry in the background plasma. In particular, in high-power, beam-heated cases the particle and energy densities in the fast ions can be comparable to that in the background thermal plasma. Then, since the fast ion density tends to be largest on the toroidally inner side of a flux surface where the magnetic field is highest and the circulating fast ions move the slowest, the electron density and the potential should become peaked there as well. In turn, the induced potential variation within a flux surface should cause the impurities (*e.g.*, Carbon) in the plasma to peak on the toroidally outer side. These processes can also cause the density of thermal ions to vary within a flux surface.

While the effects of these possible asymmetries are mostly predicted to be benign, there could be a significant effect on the D-D and D-T neutron production rate. Namely, while the TRANSP code takes account of the asymmetry in the fast ion density distribution, the thermal ions are assumed to be homogeneously distributed on a flux surface. Indications [1] in TFTR beam-heated and/or strongly rotating plasmas that the neutron production rate profile may be shifted inward slightly in major radius and that the overall neutron production rate is not always correctly predicted in these cases has led us to consider the possible role of beam-induced asymmetry effects. The possible magnitudes of the asymmetries induced by the anisotropic fast ion component, large toroidal flows and other processes, and their possible effects in TFTR fusion plasmas will be discussed.

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Gyrofluid and Kinetic Calculations in Toroidal Geometry*

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The extension of resistive magnetohydrodynamic (MHD) calculations to high temperature regimes applicable to present and future devices requires additional physics, such as particle orbit effects (finite Larmour radius—FLR), particle trapping, and wave-particle resonances (Landau damping), not found in the usual MHD models. One of the approaches in this endeavor explicitly incorporates some of these effects into fluid models by adding new terms to the moment equations[1,2]. The present and anticipated advances in computing resources, however, due mainly to massively parallel architectures and new algorithms, make it also possible to move towards 3D particle simulations in realistic geometries, with a potential capability for long-time-scale simulations, usually found in the domain of fluid calculations. Our ongoing efforts in these areas and preliminary results will be discussed.

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RADIATIVE CONDENSATION AND BOUNDARY CONDITION EFFECTS IN TOKAMAK EDGE TURBULENCE*

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The impurity radiation drive used in the temperature equation when calculating thermally driven turbulence behavior can be written in two parts. One part, the thermal instability drive, multiplies the temperature fluctuations themselves and the second part, the radiative condensation term, is of opposite sign to the first and multiplies the density fluctuations. Thus, in order for the radiative condensation term to be destabilizing, the density perturbation must be of the opposite sign to the temperature perturbation. When this was accomplished by invoking pressure balance, the radiative condensation term was found to have a large effect (Ref. 1). However, it was then found that pressure balance was not valid except at large distances from the rational surface. When this condition was relaxed, the condensation term gave a stabilizing contribution (Ref. 2). We report work here where we include the diamagnetic terms in the Ohms law. In this case once again the condensation driven can be large with the drive proceeding through the density diamagnetic term. Nonlinear calculations which depend heavily on this mechanism give fluctuation levels of 10%-50%. Both analytic and numerical work will be presented.

Work has also been started to understand the role of the limiter on thermally driven fluctuation levels. A new computer code (SOL) has been constructed for this purpose. It time advances thermal drift wave equations with boundary conditions other than periodic along a field line. Results will be presented.

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

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Symplectic Kick Maps for Arnold Diffusion and Explosive Instability in Plasmas*

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We study the effect of chaos on the three-wave explosive instability in a beam-plasma system. Chaos is generated by interaction with other waves. In the absence of exact resonance, small perturbations appear initially to be stable, but chaotic diffusion allows wave amplitudes to grow until explosive instability occurs. The existence of both thin-layer and thick-layer diffusion is demonstrated under very general circumstances. We follow the time evolution using explicit symplectic polynomial mappings, derived using Lie transformations. Numerical results for diffusion rates are compared to theoretical estimates.

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Dielectric response and fluctuations in gyrokinetic plasma*

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A detailed discussion of linear response and infinitesimal fluctuation theory for gyrokinetic systems is presented for both equilibrium and turbulent situations. A gyrokinetic fluctuation-dissipation theorem is deduced and used to predict thermal equilibrium fluctuation spectra for both electrostatic and weakly electromagnetic gyrokinetic plasmas in the limit of weak coupling. The results are interpreted physically by introducing a new concept called the "gyrokinetic vacuum," whose large relative permittivity embodies the effects of the polarization drift. The calculations are performed entirely with gyrokinetic response functions, thus distinguishing the work from previous calculations. The relation of the gyrokinetic dielectric to the conventional Vlasov dielectric is elucidated. The previous unusual result of Krommes *et al.*[1] for the electrostatic equilibrium gyrokinetic fluctuation spectrum is recovered, although in a quite different form now endowed with substantially more physical interpretation. A nonrelativistic covariant formalism is used to derive the electromagnetic results. The wavenumber power spectra of the charge density and electrostatic potential are *independent* of the plasma pressure β, while those of the parallel current, parallel vector potential, and perpendicular magnetic field are *increasing* functions of β. The latter result disagrees with previous assertions that finite β should *reduce* the fluctuation level. The source of this disagreement is isolated and the consequences of the new results for practical gyrokinetic simulations are discussed.

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Turbulent Ion Transport in the General Toroidal Geometry*

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Earlier studies of turbulent electron transport[1] in tokamaks are changed to the study of turbulent ion transport. Due to the low frequencies and large space scales of the ion motion compared with the electron motion it is now necessary to include a global model of the toroidal geometry. We start with the poloidal flux function $\psi_p(R,Z)$ and the poloidal and toroidal angles ϑ and φ for a general equilibrium with an electrostatic potential Φ.

The guiding-center particle code in the magnetic coordinates of (ϑ,φ) and conjugate $P_\vartheta, P_\varphi)$ are solved to study the test particle transport problem in the turbulent electric field. The variables of $\psi_p, \rho_\|$ are related to $P_\vartheta, P_\varphi)$ as $P_\vartheta = \left(\frac{e}{c}\right)(\psi + \rho_\| I)$, $P_\varphi = \left(\frac{e}{c}\right)(\rho_\| g - \psi_p)$. Explicitly the equations of motions are $\dot{\varphi} = \beta_1\alpha_2 \frac{\partial B}{\partial \psi_p} + \beta_2\alpha_4 + \beta_3\alpha_2 \frac{\partial \Phi}{\partial \psi_p}$, $\dot{\theta} = \beta_1\alpha_1 \frac{\partial B}{\partial \psi_p} + \beta_2\alpha_3 + \beta_3\alpha_1 \frac{\partial \Phi}{\partial \psi_p}$, $\dot{\psi}_p = -\beta_1\alpha_1 \frac{\partial B}{\partial \vartheta} - \beta_3\alpha_1 \frac{\partial \Phi}{\partial \vartheta}$, $\dot{\rho}_\| = -\beta_1\alpha_3 \frac{\partial B}{\partial \vartheta} - \beta_3\alpha_3 \frac{\partial \Phi}{\partial \vartheta}$ where α and β's are defined elsewhere. The turbulent field is represented by Φ.

When the large aspect ratio tokamak with the circular cross-section of $\mathbf{B} = \left(\frac{B_0}{1+\varepsilon\cos\theta}\right)\left(\frac{\varepsilon}{q}\hat{\theta} + \hat{\phi}\right)$ are assumed, then the explicit magnetic coordinates are obtained as $\vartheta = \theta + \varepsilon\sin\theta$, $\vartheta = \phi + I_0 q\varepsilon\sin\theta - qL_p$ where θ, ϕ are the toroidal coordinates. The function I is defined as $I(r,\theta) = \int_0^\theta d\theta(1+\varepsilon\cos\theta)^{-1} \equiv \theta I_0 + I_p(r,\theta)$.

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* *Work supported by NSF-KOSEF Grant and the U.S. Department of Energy*

SELF-CONSISTENT GENERATION OF SHEARED FLOW AND STABILIZATION OF RALEIGH-TAYLOR CONVECTION CELLS*

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It has recently been demonstrated that convection cells are unstable to a shear flow instability which evolves to a final state with a stratified shear layer.[1] In these calculations the convection cells were undriven, i.e., flow pattern was specified as initial condition.[1] We have studied the self-consistent nonlinear development of convection cells and generation of shear flow in 2-D Raleigh-Taylor (R-T) unstable plasma in a straight magnetic field. Rapid growth of the unstable R-T convection cells is arrested as the cells generate strong sheared flow. Results on the reduction of transport due to the generation of shear flow will be presented.

*Work supported by the Department of Energy.

**U.C.S.D.

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Numerical Instability in a 2D Gyrokinetic Code Caused by Divergent $E \times B$ Flow [1]

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Here we report the discovery and analysis of, and the remedy to, a numerical instability in a 2D electrostatic gyrokinetic code. This instability was first observed in our 2D electrostatic gyrokinetic code; it should also be present in some form in other types of particle–in–cell simulation codes that employ guiding center drifts. The instability prevents sensible code operation in perhaps the simplest of all test cases: cold ions and adiabatic electrons, obliquely propagating sound waves, with ∇n_0, $\nabla T_{e0} = 0$. Clean ion sound waves, with energy well conserved are observed only with kx = ky (plus or minus or both). All other modes exhibit either growth or decay. In general, an oscillation can accompany the growth, i.e, the mode frequency is complex, but this feature is dependent on the location of the particle relative to the grid. The instability persists when using many particles per cell, and we show that nonzero growth can remain in the continuous limit— undersampling is not the cause.

For the cold ion limit, a perturbation analysis of the instability is given and its results agree quantitatively with the observations from the gyrokinetic code in all respects. The basic mechanism is a false divergence of the $E \times B$ flow caused by the interpolation between the grid and the particles as coupled with the specific numerical method for calculating $E = -\nabla\phi$. Stability or instability depends in detail on the specific choice of particle interpolation method and field method. One common interpolation method, subtracted dipole, when coupled with a 2-point difference for E, is stable. We believe that most of the gyrokinetic simulation results reported to date have used this stable method. Other commonly used interpolation methods, linear and quadratic, are unstable when combined with a finite difference for the electric field. Linear and quadratic interpolation can be rendered stable (oscillatory) if combined with another method for the electric field, the analytic differential of the interpolated potential.

Analysis of the single particle particle per cell limit was done with Mathematica, mainly to keep track of the many terms that arise— linear interpolation coupled with a two point difference for E results in 64 separate terms; quadratic interpolation results in 324 terms. An independent analysis of the continuous limit agrees in detail with the integral of the single particle per cell results.

There are methods stable in the continuous limit but unstable in the single particle per cell limit; one example is linear interpolation coupled with a 6-point difference for E— this result was also independently derived by A. B. Langdon; given a specific interpolation method, his techniques allow him to derive a difference scheme for E that renders the method stable in the continuous limit. These methods can not be recommended as perfectly stable.

Major differences have been observed in our gyrokinetic code for thermal ion runs when replacing our former unstable method with our stable method[3].

[1]Performed by LLNL for USDoE under contract W-7405-ENG-48.
[2]Deceased
[3]L. Lodestro, T. Williams, private communication

Stability of the Low-n TAE Modes*

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For large aspect ratio, concentric circular, zero beta tokamaks, the lowest Alfvén continuum gap occurred at location $r=r_o$ where the safety factor is given by $q(r_o)=(2m+1)/2n$. The gap center frequency at r_o is given by $\omega_o \approx V_A/2q(r_o)R$, where m and n are the poloidal and toroidal mode number, respectively. The gap width is proportional to the inverse aspect ratio r_o/R. As m and n become larger, the continuum gaps become densely populated radially so that they form a continuous radial structure. If the gap does not line up across the minor radius, the TAE mode will experience continuum damping. Analytical expression will be given for the continuum gap structure due to finite plasma beta and shaping effects. In general, the plasma beta and shaping effects will lift the gap center frequency higher and enlarge the gap width. On the other hand, as the plasma beta increases or the magnetic shear decreases, the TAE frequency will move downward into the lower continuum and the TAE mode suffers heavy continuum damping.

Continuum damping effect on the TAE modes will be studied numerically with the NOVA-R code[1] -- a resistive MHD version of the NOVA code. Once the continuum damping rate is computed for a TAE mode, this information will be used in a perturbative analysis (NOVA-K)[2] involving alpha particle instability drive and core plasma Landau dampings to determine the stability boundaries in the parameter space of α-particle beta β_α, α-particle pressure gradient parameter (ω_*/ω_A) (ω_* is the α-particle diamagnetic drift frequency), and (v_α/v_A).

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TOROIDAL AND TRAPPED ION ITG MODES WITH ANISOTROPIC η_i.*

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The effects of anisotropic η_i on the lab branch of ITG mode has been reported earlier.[1] The effects of anisotropic η_i on the toroidal and trapped ion ITG modes are now studied. For the toroidal mode, fully kinetic ion response in the presence of magnetic drifts and a dissipative trapped electron response are used. Strong differences in the roles of $\eta_{i\parallel}$ and $\eta_{i\perp}$ are seen and a second stable regime is found. For the trapped ion ITG mode, use of kinetic trapped ions with magnetic drifts and collisions and dissipative trapped electrons yield far less dramatic differences. Lastly, a theoretical model for an experiment on the transition of the slab branch to a toroidal/trapped ion branch in the Columbia Linear Machine will be discussed.

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A MODEL FOR DISSIPATIVE TRAPPED ELECTRON MODE TURBULENCE WITH ION LANDAU DAMPING AND FINITE LARMOR RADIUS EFFECTS*

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Trapped electron modes may be one of the causes of deterioration of confinement in toroidal plasmas. We have implemented a model to study the turbulence of the dissipative trapped electron mode[1] in slab geometry. The electron dynamics include a non-adiabatic piece modeled with an *i*-delta-type response in addition to the usual adiabatic part. The ion dynamics include Landau damping and FLR corrections.[2,3,4,5] In the paper by Hedrick et al.,[6] the different approximations and the corresponding pseudo-potentials are discussed. In this paper, we present the linear numerical results of the model evolution equations for the different approximations to the plasma dispersion function and the finite ion Larmor radius effects. The numerical results were obtained using a shooting technique. A scan of the range of unstable modes has been done considering TEXT-like parameters. We found that nonlinear studies for these parameters can be done using our model. If available, nonlinear results will be presented.

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EDGE PLASMA CONFINEMENT IN A FIELD-REVERSED CONFIGURATION*

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As with tokamaks, the edge plasma in a field-reversed configuration (FRC) is believed to have a strong influence on the global confinement. In the terminology used here, *global confinement* refers to the plasma as a whole (both particles and energy), and *edge confinement* refers to the edge plasma proper where losses result from flow or related processes along open field lines. Anomalously good edge confinement is inferred from experimental FRCs. First, the edge confinement of particles was found to be several times longer than predicted by fluid models.[1] Second, the electron thermal loss could not be described by classical parallel thermal conductivity, and in fact was somewhat lower.[2] In both cases, common experimental conditions were such that fluid models with thermal conduction might be thought to apply. Preliminary explanations for these anomalies are as follows. (1) Ion motion in the low-magnetic field region near the x-points (magnetic well) is highly non-adiabatic, and the magnetic moments experience an effective scattering. This alters the flow through the magnetic well in such a way that the rising magnetic field downstream from the well exerts a throttling effect which limits the flow rate. (2) Though typical FRC plasmas are moderately collisional, a significantly higher degree of collisionality is required for classical thermal conductivity to apply. Instead, electrons are electrostatically confined much as in mirror devices, and the loss rate is convective, i.e. a few times kT_e of energy is carried away with each electron which is lost. The physics of such edge processes will be examined using various means. These include the double-adiabatic model, and kinetic models.

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Loss of Passing Energetic Particles due to Low Frequency, Low–n MHD*

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Earlier studies of the loss of energetic particles by low–n MHD perturbations have shown both that trapped particles can be transported by low-frequency perturbations ($\omega \lesssim 10$ kHz)[1] in a manner fully analogous to ripple loss due to TF ripple, and also that passing particles can be transported by high frequency ($\omega \sim 100$ kHz) perturbations such as TAE modes.[2,3] Here, we show numerically and analytically that low-frequency MHD may also transport passing particles, a new instance of the same general stochastic mechanism. We present analytic expressions for the stochastic threshold and for the diffusion coefficient operative when that threshold is exceeded, which applies to transport by TF ripple, low and high- frequency MHD, and to passing as well as trapped particles.

For single helicity low-frequency, low-n modes, one finds that the stochastic threshold for passing particles is at the upper end of levels one expects to observe experimentally, $\tilde{b} \equiv B_r/B_0 \gtrsim 10^{-3}$, similar to the earlier result[1] for trapped particles in low-ω MHD, and more recently[3] for passing particles in high-ω MHD. Very large (but possibly attainable) amplitude perturbations can exceed the threshold, resulting in major loss of both trapped and passing alpha-like particles. Moreover, the presence of multiple modes, or multiple poloidal components of a single mode, can lower the threshold, making such loss more likely. For typical perturbation amplitudes, below the stochastic threshold, loss will be more limited, but still large enough to be of concern, increasing loss of alpha-like particles on TFTR, for example, to several times above the quiescent level.[4]

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Ballooning Stability Analysis and Optimization of Tokamak Equilibria*

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High beta, high bootstrap current plasmas are of interest to small steady-state tokamaks which are under consideration for testing divertor and blanket technologies. For the purpose of studying such plasmas, free boundary equilibrium, ballooning stability, and poloidal field codes have been upgraded to include q-solver and J-solver capabilities, pressure profile optimization, and a bootstrap current model. By applying a bicubic spline representation to the two dimensional equilibrium, and a new "local" technique for integrating the ballooning equation, these codes have been tailored to study stability near the separatrix accurately and efficiently.

In the present work, we consider the pressure profile optimization for ballooning stability in equilibria similar to those found in the DIII-D high beta and VH-mode regimes. In these calculations, the sensitivity of the ballooning stability to the pressure gradient near the separatrix is shown. The effect of aspect ratio on such ballooning optimal equilibria, with both the first and second stability characteristics, is also studied.

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Nonlinear Evolution of Internal Kink Modes in the Collisionless and Semi-Collisional Regime

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The internal kink mode plays an important role in sawtooth dynamics in tokamak plasmas and is sensitive to kinetic effects as well as local pressure gradients and magnetic shear. Kinetic effects such as finite gyroradius and wave-particle interactions are difficult to incorporate in nonlinear MHD simulation models and therefore we have constructed and used 3D gyrokinetic particle-in-cell simulation models in order to address questions about kink mode stability and dynamics in the collisionless and semi-collisional regimes. A previously-described 3D model[1] in cylindrical-type geometry has been extended to include perpendicular magnetic perturbations from parallel currents and inductive electric fields. The fundamental plasma scales of the model are the ion gyroradius (ρ_1) and the collisionless skin depth (c/ω_{pe}) and energy and momentum conserving electron-ion collisional scattering is incorporated to give a finite resistivity. We have verified the presence of collisionless and semi-collisional (m,n) = (1,1) internal kink modes and growth rates and stability thresholds follow closely the theories of Basu and Coppi and Porcelli[2]. Starting with model cylindrical equilibria and $q_o < 1$, the basic picture of Kadomtsev reconnection is obtained by the time scales are much more rapid due to the c/ω_{pe} scale and rapid growth rate of the instability in the semi-collisional and collisionless regime[3]. Local parallel electron distribution functions are measured inside and outside the island and a skewness is found. The inductive electric field is measured and found to be larger than the Drecier field. The effects of thermal gradients as well as effects of trapped electrons and energetic particles will also be presented.

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Graph Massage, an Improved Technique in Moving Finite Elements

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We describe a new capability called graph massage which has been added to Moving Finite Elements to enhance its natural ability to adapt grids for treating difficult problems in computational fluid dynamics. Moving Finite Elements (MFE) is a recently developed numerical method that can be applied to a large class of nonlinear, time-dependent fluids problems. Consider the general PDE

$$\mathbf{u}_t = \mathbf{L}(t, \mathbf{x}, \mathbf{u}),$$

where $\mathbf{u}$ is a vector of dependent variables, $\mathbf{x}$ is a 2-D vector of independent variables, and $\mathbf{L}$ is at most a second order differential operator. The finite elements are piecewise linear triangular facets, whose vertices are advanced in x-u space so as to minimize the variational

$$I = \int (\mathbf{u}_t - \mathbf{L})^2 w d\mathbf{x},$$

where w is a specially-chosen weight function. The resulting ODE's for node position and amplitude cause these quantities to move smoothly together, allowing time steps that may exceed the CFL limit by a large factor when a stiffly stable ODE solver is used.

While the instantaneous movement of the nodes is optimal with respect to the variational, as described above, node depletion and excessively long triangles can occur in certain regions over finite time intervals. Conversely, over finite time intervals, moving shock fronts can push too many nodes into small regions. Such problems typically occur in fluids with sheared flow, large amplitude waves reflecting off a wall, and systems with changing topology, such as magnetic reconnection.

These difficulties are resolved by the graph massage algorithm which incorporates creation and annihilation 'modules' to assess the acceptability of the grid and, if necessary, alter the grid by doing single node additions/deletions only where needed. The modules are designed to 1) interact 'fruitfully' with each other, 2) produce an output gridding that is acceptable even if later perturbed by small amounts, 3) keep deformation of the manifold (due to annihilations) to within user-specified tolerances. Continuous grid motion according to the standard MFE algorithm minimizes the need for graph massage. Graph massage guarantees a robust method for the solution of the challenging fluids problems typical of Magnetic Fusion Energy plasmas.

Solutions to several fluids problems will be presented, featuring 3-D color movies specially developed for MFE.

The Realizable Markovian Closure:
A Statistical Approximation for Drift-Wave Turbulence

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A well known Markovian statistical closure for turbulence computations, derivable from the direct-interaction approximation (DIA), is shown to be potentially *nonrealizable* in the presence of the linear wave phenomena encountered in plasma physics and geophysics. This statistical closure is a type of eddy-damped quasi-normal Markovian (EDQNM) approximation in which the triad interaction time is obtained not from a phenomenological model but from the use of a Fluctuation-Dissipation (FD) relation in the DIA equations. This choice accounts for the nonlinear renormalization of both the frequency and the damping rate. For the EDQNM, a violation of realizability can have serious physical consequences, including the prediction of negative or even divergent energies. None of these difficulties arise when this closure is applied to the fluid problems for which it was originally designed. A new statistical approximation for wave turbulence, the realizable Markovian closure (RMC), is proposed as a remedy. The RMC is based on a form for the Fluctuation-Dissipation (FD) ansatz more suitable than the one conventionally used to derive the EDQNM. This form is appropriate for nonstationary systems and it reduces to the classical FD Theorem in equilibrium. An underlying Langevin equation is exhibited for the RMC. No assumption of white-noise statistics is made in the construction of this Langevin equation; thus, even in the wave-free case the RMC appears to provide a better representation of the true dynamics than does the EDQNM closure. The RMC is tested numerically for a system of three interacting waves. Although the steady-state forms of both closures agree, the RMC exhibits improved transient behaviour. An anisotropic generalization of the isotropic wavenumber partitioning scheme pioneered by Leith and Kraichnan [1972] is developed; this is used to obtain steady-state solutions of the RMC and DIA closures for two-dimensional models of drift-wave turbulence based on the Hasegawa-Mima and Terry-Horton equations. The closure predictions compare well to spectra obtained by conventional pseudo-spectral methods. The numerical value for the particle diffusion coefficient is found to be more than an order of magnitude higher than a simple mixing-length estimate.

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Toroidal Mode Structure of Long Wavelength Microinstabilities*

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A realistic assessment of the influence of long-wavelength microturbulence on transport and confinement in tokamak plasmas is both a fundamentally important and a practically relevant problem. Previous evidence from scattering measurements of fluctuations has generally indicated that the largest amplitudes occur at the longest measurable wavelengths ($k_\theta \rho_i < 0.2$, with ρ_i being the ion gyroradius). The recent implementation of new diagnostics (beam-emission spectroscopy and reflectometry) capable of measuring long-wavelength fluctuation properties in major devices such as TFTR has greatly heightened interest in testing as well as developing theoretical models of such phenomena. In addition, results from empirical confinement time scaling studies have indicated that Bohm-like trends (characteristic of long-wavelength modes) could be supported. Motivated by the preceding considerations, we have analyzed the fully 2D (r, θ) mode structures for long-wavelength electrostatic microinstabilities such as trapped-ion modes and toroidal ion temperature gradient (ITG or η_i) modes. For TFTR-like parameters, large radial structures (nearly 50 ion gyroradii in extent) have been calculated using a comprehensive toroidal finite-element code[1] capable of evaluating large scale kinetic behavior extending over many rational surfaces. These investigations provide important information on the mode structure, unstable spectral range, *etc.* needed to help construct realistic nonlinear models governing long-wavelength turbulence. Moreover, they can serve as a valuable self-consistent benchmark for toroidal eigenmode structures obtained from the linearized versions of gyrokinetic and gyrofluid simulation codes. Qualitative trends, implications, and the possible sensitivity of these modes to sheared toroidal flow effects will be discussed.

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Two-Fluid MHD Description of the Internal Kink Mode in Tokamaks*

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Abstract

The two-fluid linear MHD theory of the internal kink mode is studied. In contrast to previous investigations, terms containing the divergence of the electron velocity are not neglected in the derivation of the perturbed longitudinal Ohm's law. It is found that these terms significantly modify the predictions of the two-fluid theory in the parameter regime relevant to recent high-temperature tokamak experiments, in which the scale-length of the current layer in the resonant region is smaller than the ion Larmor radius. Furthermore, these modifications put the predictions of the two-fluid theory in good agreement with the results of kinetic studies, suggesting that the relatively simple two-fluid MHD theory provides an adequate description of the $m = 1$ mode. In particular, two-fluid MHD may serve as a good model for numerical simulations of current experiments, in which one-fluid MHD is not relevant. An important feature of the two-fluid theory is that, in contrast to one-fluid MHD, the Hall term decouples the ion motion from the magnetic field in the parameter region mentioned above, thereby allowing the characteristic scale of the plasma motion to differ from that associated with the current sheet in the resonant layer. Consequently, the characteristic scale of plasma motion, which is in fact the "ion-sound Larmor radius" ρ_s, does not (with certain restrictions on the drift frequencies) fall below the ion Larmor radius ρ_i. This prediction of the two-fluid theory may account for its agreement with kinetic results, and also simplifies the numerical description of plasma motions in the resonant region relative to one-fluid MHD models. Using the large scale length for the plasma motion in Kadomtsev's reconnection model leads to the approximate reconnection time $\tau = \tau_A^* a_{1/1}/\rho_s \sim a_{1/1} R\sqrt{n}/\sqrt{T_e + 5/3T_i}/(1 - q_0)$.

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Simulation of Lower Hybrid Current Profile Modification Experiments in PBX-M and JET*

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Current profile modification experiments using lower hybrid current drive are being carried out in PBX-M and JET. To simulate these experiments requires a code that is time dependent, uses non-circular equilibrium and includes the beam driven and bootstrap currents in addition to the current driven by the lower hybrid system. We have developed a modified form of the BALDUR code which contains the Bonoli/Englade [1] lower hybrid package. The latter package does 3-D ray tracing and solves a 1-D Fokker-Planck equation for the electron distribution function.

We have investigated scenarios which would create q(r) profiles that facilitate stable entrance into the second stability region at low current ($I_p \leq 200$ KA) in PBX-M. These profiles feature high q_0 and broad current profiles. They also contain substantial bootstrap current fractions. These simulations support experiments being planned.

We will also present LHCD simulations of current drive experiments that were performed in JET.

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APPLICATIONS OF THE QUIET IMPLICIT PIC METHOD

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Recent one- and three-dimensional particle simulation results using the QIP method are described. In this approach, a fully kinetic plasma is represented by using PIC methods for only the deviation of the unknown distribution function from a local Maxwellian with the same low-order moments. One-dimensional calculations have investigated the consistency and accuracy of the method for low-frequency plasma waves. A new approach, in which the distribution information carried by the individual simulation particle orbits is used to construct the local Maxwellian, will be discussed. In this approach, the moment equations are used only to estimate the time-advanced electromagnetic field in a consistent and numerically stable manner. All information concerning the distribution is carried by the orbit information. This eliminates earlier difficulties associated with the desyncronization of the independnet orbit and moment information. At the same time, a three-dimensional, straight-torus version has been developed and applied to MHD instabilities in a tokamak. Initial results for the $m = 1$ internal kink (sawtooth) are presented.

Stability Analysis of the Internal 1/1 Mode in Tokamaks and Limitations of the Resistive MHD Model.

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The MHD stability limits of TEXTOR profiles, found experimentally to be marginally stable, have been studied using both PEST3 and an initial value code, ARES. Specifically, we consider the ideal and resistive stability properties of the 1/1 internal mode when $q<1$ over some fraction of the minor radius. We find that equilibria obtained using the measured pressure and q profiles are stable to the ideal 1/1 mode. However, these equilibria are always linearly unstable to resistive modes when the fluid compressibility is finite. Stable regions can be found with the assumption of incompressibility, but only when the shear at the $q=1$ surface is very small, when the aspect ratio of the $q=1$ surface is small and the Lundquist number, S, is large.

Our confidence in both the experimental data and the computational results lead to the conclusion that the usual single fluid, resistive MHD model does not correctly predict the observed 1/1 mode marginal behaviour. The effects of transport, imperfect magnetic topology etc. could be the reason for the discrepancy.

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Saturation of Alpha Particle Driven Alfven Wave Turbulence Through ion Compton Scattering*

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Nonlinear saturation of alpha particle driven Alfven wave turbulence through bulk ion Compton scattering is investigated. The investigation is based on the consideration that the alpha particle density gradient which provides the free energy source for the Alfven wave fluctuations may be maintained by external particle source even in the presence of Quasi-Linear particle diffusion. The ion Compton scattering is found to conserve the total fluctuation energy but induce a turbulence spectral shift in k_θ space towards high k_θ. This spectral shift reduces the power transfer between the α particles and the Alfven wave fluctuations, and leads to saturation of turbulence. Fluctuation levels for both $e\tilde{\phi}/T_e$ and $\tilde{B}_r/B$ have been obtained. Turbulent particle transport corresponding to *Mixing Length Estimate* have also been obtained. The implications of the results to both α particle and bulk plasma confinement will be discussed.

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Solution of Edge Plasma Transport Equations by a Mapping Technique

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A novel numerical mapping technique has been developed to facilitate the solution of edge plasma transport equations. The region of interest is a thin boundary layer containing the separatrix, in a diverted tokamak configuration. This layer is mapped into a much thicker layer, which greatly reduces the difficulty of dealing with the large disparity in parallel and perpendicular transport rates. The mapping procedure preserves the topology, in contrast to other techniques which map the regions inside and outside the separatrix separately. The geometry and poloidal magnetic field are defined by MHD equilibrium fits to particular DIII–D shots. For simplicity, the ion heat equation is considered by itself. It is solved in the transformed variables, using a 2-D finite element method, and the inverse mapping is used to obtain the solution in the original variables. The results of the calculation show that the constant temperature contours closely follow the flux surfaces except near the x–point, where they depart significantly from them. With the ion grad–B drift toward the x–point, in a single-null configuration, the peak in the heat flux to the divertor plate shifts strongly to the inboard side, while with the opposite direction of the toroidal magnetic field, it shifts strongly to the outboard side.

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X-point effects on particle orbits and neoclassical transport.

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Traditionally neoclassical transport assumes a poloidally constant poloidal magnetic field. Near an X-point the poloidal field is very small, so the field lines linger at that poloidal location. This is shown to modify particle orbits, enhancing grad B drifts. In particular banana orbits that bounce near the X-point have "square tips", due to the grad B drift acting on the particle a longer time. Computational and analytical calculations of particle orbits allow an evaluation of the importance of this effect (the drifts are proportional to $v_{thermal}$, so hotter ions are more strongly affected). Realistic poloidal fields are used to compute particle orbits.

A study of changes in Pfirsf-Schluter collisional transport due to the X-point will also be presented.

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Anomalous Electron Pinches in Hot Electron Plasmas

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Recent experimental results on ECH heating in DIII–D [1] have concluded that an electron energy pinch may be necessary to explain the insensitivity of the electron temperature profile to ECH heating location. In the ECH experiments $T_e \gg T_i$, $\eta_e \gg \eta_i$, with $\nu_* \gtrsim 0.2$ so that it is reasonable to assume that electron-driven instabilities will be dominant. The existence of a pinch is difficult to understand, at least in the framework of quasilinear theory, since there is no known electron instability that can drive an inward pinch (of either particles or energy) in the parameter regime of interest. However, it has been recently pointed out [2] that a more accurate treatment of the turbulent collision operator (the turbulent Lenard-Balescu operator) will obtain both particle and energy pinch terms. These results apply to general geometry but are restricted to stable plasmas. Here we discuss a complimentary situation, an unstable plasma in a simple slab geometry. Using a simple $i\delta$ model for electron drive, anomalous diffusive and drag terms (arising from discrete turbulent structures or "clumps") are evaluated. This procedure is analogous to early work in a turbulent unmagnetized plasma [3] in which quasilinear theory was generalized to include discreteness effects. The magnitude and scaling of the clump-induced particle and energy pinches, for this model electron-driven instability, will be discussed in terms of the ECH heating experiments.

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ß-limit Evaluation for the TJ-IU Torsatron

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TJ-IUpgrade is a six period, l=1 torsatron in the final stages of construction at CIEMAT, Madrid. Its major radius is 0.6 m and plasma radius 0.1 m. The device's main purpose is to serve as a bridge between the experiments being conducted at the TJ-I Tokamak and the future experiments on the Heliac TJ-II that will start operation in 1995. For this reason, TJ-IU, like TJ-II, was designed as an almost shearless device and its main stability mechanism lays then, on the magnetic well created through a change in the winding law of its helical coil:

$$\Phi = 1/6\ (\theta + 0.4 \sin \theta).$$

Start-up and heating will be done with a 200 kW, 28 GHz gyrotron working at the second harmonic (0.5 T) and an ICH system is under design. Initial operation is expected in June 1992.

In this work , the 3-D stability behaviour to Mercier modes is presented for the two main operating scenarios foreseen, the standard one with the magnetic axis at its nominal position, 0.58 m, and the "inward" one with the magnetic axis 6 cm towards the center. We have chosen Mercier modes as the most ß-limiting modes to stellarator configurations but an analysis is under way to check the obtained ß-limits to ballooning modes. Preliminary studies show that the two scenarios have particle orbits with confinement properties opposite to stability properties. At the standard position the device is totally stable to Mercier modes to the achievable ß's with the initially available ECH power (< 1%) but its stability limit tends to zero as we push the magnetic axis inward destroying the vacuum magnetic well. Kinetic effects on stability due to the specific creation of high energy particles in the device in the "inward" position could be, then, experimentally checked. A detailed analysis of the theoretical work leading to these conclusions will be presented.

Quasi Three-Dimensional Electron Holes in Magnetized Plasma*

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Kinetic effects associated with the electron motion parallel to the magnetic field lines, in a low β plasma ($\beta << m_e/m_i$, where β is the ratio of thermal and magnetic pressures) are studied using the gyrokinetic description of electrons, and hydrodynamic description of ions. In the hydrodynamic limit these equations reduce to Strauss' equations of reduced magnetohydrodynamics (RMHD), with the main nonlinearity arising from the fluid drift motion, which is acting strictly perpendicular to the magnetic field, and leading to the creation of coherent structures in the form of double vortex flutes.

We construct a self-consistent (BGK) solution of the full nonlinear system, and demonstrate that fluid vortex flutes are not destroyed on the long time scale in the interaction with resonant particles. A new type of stationary solution becomes possible, in the form of an electron hole which is strongly elongated along the magnetic field, and whose localization in the perpendicular direction is determined by fluid nonlinearities. This new type of coherent structure may play an important role in transport processes in open ended machines, such as magnetic traps.

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The Asymptotic Spectrum of a Viscous 2-D Turbulence*

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The asymptotic spectrum of enstrophy at large wave number (k) is derived in the viscous as well as in the inertial range for the Hasegawa-Wakatani equations modified by the inclusion of classical density diffusion. The enstrophy obeys an equation independent of the adiabaticity; its spectrum is $K_1(\eta k)/k$, where K_1 is the first order modified Bessel functions of second kind, $\eta \equiv \sqrt{2C_2/D_{xx}}$, C_2 is a measure of the viscosity and D_{xx} is the self-consistent diffusion coefficient. For $C_2 \to 0$, the expression reduces to the previously obtained inertial range formula $1/k^2$. We have also solved the problem numerically. The simulations have been carried out for large enough values of k ($k_{max} = 25$) with 171 x 171 grid points to warrant a meaningful comparison with theory.

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A Fully Nonlinear Characteristic Method for Gyrokinetic Simulation*

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We present a new scheme which evolves the perturbed part of the distribution function along a set of characteristics that solves the fully nonlinear gyrokinetic equations. This nonlinear characteristic method is similar to the weighting schemes for linear[1], partially linear[1], and δf simulations[2,3]. The added feature here is that this new scheme enables us to keep all the nonlinearities, particularly those associated with parallel acceleration, while preserving all the conservation properties of the original system. As such, one can take advantage of the low noise property of the weighting scheme together with the quiet start techniques to simulate weak instabilities. The number of particles one uses for these studies could be orders of magnitude smaller than those simulating the total distribution function. In this paper, the basic algorithms of the scheme are discussed along with their applications to the simulation of one-dimensional drift wave instabilities. Good agreement, in terms of the linear mode frequency and growth rate, and nonlinear saturation amplitude due to velocity space trapping, has been obtained between the simulation results and the theoretical predictions. However, the results also indicate that the total energy is not well conserved at the initial stage of the simulaton, and the conservation improves only when there is sufficient number of particles and the fluctuation amplitude is appoaching the thermal noise level of the simulation plasma. Further investigation of the conservation properties in multi-dimensional simulation is needed to provide the guideline for the number of particles one should use for the steady state simulation of microinstabilities. The algorithms applied to the more general electromagnetic gyrokinetic equations will also be discussed.

0* Work supported by the DOE Fusion Postdoc Program and DOE Contract No. DE-AC02-76-CHO-3073.

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Abstract for the Sherwood Fusion Theory Conference
April 6-8, 1992

Resonant Pfirsch-Schlüter Currents and Equilibrium Magnetic Island Formation

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Pfirsch-Schlüter currents are known to produce magnetic islands in non-zero beta, three-dimensional, magnetostatic equilibria. A number of authors have analytically computed self-consistent magnetic island widths due to resonant Pfirsch-Schlüter currents.[1-3] Most magnetic island calculations presume that as the island forms, the pressure is constant inside the island separatrix, while pressure gradients exist on magnetic surfaces outside the separatrix which is caused by a diffusion process and a pressure source away from the island region. However, if a pressure source is introduced inside the island separatrix, a pressure gradient and the corresponding Pfirsch-Schlüter currents can arise on magnetic surfaces within the island separatrix. An analytic model is introduced which couples a self-consistent island width calculation from Ampere's Law with a pressure profile calculation due to a sourced transport equation near the magnetic island region. It is found that for pressure profiles that are peaked on the magnetic axis of the magnetic island, the resonant currents cause an enhancement in the equilibrium magnetic island width.

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The Direct Interaction Approximation Applied to a Dissipative Drift Wave Turbulence Model*

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We apply the Direct Interaction Approximation (DIA) to a multi-field plasma turbulence model of dissipative drift wave turbulence. The model includes separate evolution equations for plasma density $\hat{n}$ and electrostatic potential $\hat{\phi}$.[1] A full two-time, anisotropic, multi-field DIA system is derived and solved numerically. Comparison is made between these solutions and the statistical properties calculated by directly solving the model equations for an ensemble of initial conditions.

The DIA will be shown to reproduce the "relaxation to equilibrium" which solutions to the model equations undergo when the sources and sinks of energy are removed. The DIA will also be compared to non-equilibrium simulation runs. Previous work simulating the non-equilibrium system has found a strong dependence on the parallel electron conductivity, which provides cross-coupling between the density and potential evolution equations. This dependence will be investigated with the DIA code. In the limit of small conductivity, the solutions to the model equations are known to exhibit long-lived trapped structures. We are particularly interested in probing the accuracy of the DIA in this regime. However, the complexity of the DIA limits our runs to rather coarse grids, which may make this comparison difficult. Some potential modifications which would reduce the memory usage of the DIA code will be discussed.

Based on our comparisons, we will attempt to draw conclusions about the accuracy of the DIA for this model, and about the approximations which are frequently used in deriving "simpler" closure schemes.

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THE 1992 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

CURRENT DRIVE BY LOWER HYBRID WAVES IN COMBINATION WITH FAST ALFVÉN WAVES*

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Recent experiments on JET [1] have shown that the current drive efficiency is significantly enhanced when fast Alfvén waves (FAW) are used in conjuction with lower hybrid waves (LHW). The enhancement in the current drive efficiency is a combination of two effects [2]. The first effect is the so-called JT-60 effect where the current drive efficiency increases due to an increase in the volume averaged electron plasma temperature. This happens as the FAW heats the electrons. The second effect is due to the synergism between the LHW and the FAW as the FAW interacts with the electron tail pulled out by the LHW. The synergistic effect was explained qualitatively by showing that an enhancement in the perpendicular energy of the tail electrons produced an enhancement in the current drive efficiency [3].

We will now report on results from Fokker-Planck simulations which study detailed effects of the FAW on a tail produced by LHWs and the associated current drive efficiency. In particular, changes in the perpendicular energy of the tail electrons due to the FAW will be quantified. The JET results also show that the synergism is most effective for a monopole FAW antenna whose spectrum is peaked at $k_{\|} = 0$. It is well-known that for small $k_{\|}$ the FAW can deliver some of its energy to the ion-Bernstein wave (IBW) through mode conversion at the ion-ion hybrid resonance layer. This IBW can also interact with the tail electrons. The effect of possible current drive synergism of the IBW with the LHW will also be presented.

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Abstract Submitted for the 1992 International
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Transport inferred from consideration of particle orbits in drift turbulence, P. M. BELLAN *Caltech* --Consideration of particle orbits in the quasi-2D potential blobs[1] of drift turbulence typical of tokamaks gives a gyro-Bohm diffusion consistent with global observations over a broad range of parameters in a wide variety of devices. Provided $e\tilde{\phi}/T_e > \tilde{n}/n \approx (k_\perp L)^{-1}$, this diffusion is *not* proportional to the turbulence amplitude and so will be important in the plasma interior even though interior turbulent levels are low (~1–5%). The key parameter is the blob lifetime.

Consideration of ion orbits in steep hill blobs gives a stochastic orbit threshold of $(k_\perp \rho_s)^2 (e\tilde{\phi}/T_e) \approx 0.3$, a factor of three lower than the 1-D calculation in Ref.2. Since $e\tilde{\phi}/T_e \sim 0.5$–$0.8$ is often observed in the edge, ions on edge potential hills having $k_\perp \rho_s \sim 0.6$–0.8 will be stochastically heated; such steep hills can be expected to form a non-negligible part of the turbulent edge spectrum.

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Effects of Neutrals on Tokamak Edge Plasma*

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Besides fueling a tokamak plasma, cold, stationary neutrals near the wall can cause drag on rotating ions via charge-exchange (CX). In addition, CX produces hot, penetrating neutrals that can enhance plasma viscosity and thermal conductivity, and can diminish ion diamagnetic drift[1]. A cold ion[2] population is also produced that causes further drag while being heated via Coulomb collisions with hot ions. We derive analytical expressions for the drag, viscosity, thermal conductivity and plasma rotation profiles by solving a four-population drift-kinetic model with physical boundary conditions at the wall. The resulting isotopic dependence of energy confinement and the effects of varying plasma profiles near the wall are presented.

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Effects of Flux Surface Jitter on Linear Instabilities*

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The effects on linear instabilities caused by jittering a rational flux surface about its equilibrium position are investigated. Previous work[1] is extended in two ways. First, low-beta, reduced MHD is used to determine the consequences of jitter for the m = 2 tearing mode in both the coherent and noisy cases. Secondly, the effects of jitter are incorporated into a drift-kinetic equation to determine the electron response. The Landau resonance (or equivalently, the electron adiabatic regime) can be completely eliminated for sufficiently large jitter amplitude. The effect of jitter on the m = 1 and m = 2 tearing modes is considered from this kinetic point of view.

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The Kinetic Kink Mode

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ABSTRACT.

The stability of the $m = 1$ internal kink mode is investigated in the ion collisionless regime and it is found that trapped bulk ions can strongly affect the stability threshold. When trapped particles, finite ion Larmor radius effects and the equilibrium electric field are retained in the theory of the $m = 1$, the following dispersion relation can be obtained,

$$\sqrt{-\hat{\omega}(\hat{\omega} - \omega_{*i})} = i\omega_A(\lambda_H + \lambda_{Ki}) \quad (1)$$

where λ_H and λ_{Ki} represent the "total" fluid and kinetic potential energy (following Coppi's notation [1]) and $\hat{\omega} = \omega + d\Phi_0/d\psi$ (Φ_0 is the equilibrium electrostatic potential). The fluid contribution can be written in the form given by Bussac et al. [2], and the main kinetic contribution comes from trapped bulk ions and can be written as

$$\lambda_{Ki} = (\hat{\omega} - \eta(\hat{\omega})\omega_{*i})\Lambda_{Ki}. \quad (2)$$

In an equilibrium configuration with flat density profiles the function $\eta(\hat{\omega}) \to 2$ for $|\hat{\omega}| > \omega_{Di}$ (the ion magnetic drift frequency), and $\eta(\hat{\omega}) \to 1$ for $|\hat{\omega}| < \omega_{Di}$. The term Λ_{Ki} is a complicated function of β_p, $\hat{\omega}$ and the shear at the $q = 1$ surface ($\hat{s}$). Two kinetic effects can be identified: 1) the destabilizing trapped particle magnetic drift resonance given by $Im(\Lambda_{Ki})$ and 2) the nonresonant contribution given by $Real(\Lambda_{Ki})$. The nonresonant contribution can be written as

$$Real(\Lambda_{Ki}) \simeq \frac{\beta_{pi}(0)}{\sqrt{2}\hat{s}}\left(\frac{r_s}{R_0}\right)^{5/2}\frac{\omega_{*i}}{\bar{\omega}_{Di}}H\left(\frac{\hat{\omega}_r}{\bar{\omega}_{Di}}\right) \quad (3)$$

where $H(x)$ is a transcendental function, $\beta_p(0) = 8\pi p(0)/B_\theta^2(r_s)$ and $\omega_{*i}/\bar{\omega}_{Di} \sim 1/\epsilon$. Since the function $H(x)$ is negative for $x > 4.4$, the ω_{*i} branch of the kink mode can be destabilized by trapped ions. The marginal stability has been numerically calculated and shows a surprising low threshold in β_p for the ω_{*i} branch (approximately 40% of the ideal threshold). On the contrary, the $\hat{\omega} = 0$ branch is strongly stabilized by the trapped ions showing a stability threshold much higher than the ideal. The growth rate of the Kinetic Kink Mode (the ω_{*i} branch destabilized by trapped ions) reaches a large value only well above threshold

$$\gamma_{KKM} \sim \beta_p(0)\left(\frac{r_s}{R_0}\right)^\alpha \omega_A\left(\frac{1}{1-q_0}\right) \quad (4)$$

where $1.5 < \alpha < 2.5$. Stability boundaries and growth rate plots will be presented.

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Chaotic Transport by Drift/Rossby Waves in Analogous Plasma and Rotating Fluid Systems*

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Plasma drift waves and Rossby waves, which occur in shallow water rotating systems with a topography gradient, are both described by the same well-known Charney-Hasegawa-Mima (CHM) equation. The analog of the $\mathbf{E} \times \mathbf{B}$ plasma drift velocity is the $\hat{z} \times \nabla P$ geostrophic flow, the topography gradient is equivalent to the plasma density gradient, and the Coriolis force parameter plays the role of the ion cyclotron frequency. In both systems advective transport can be studied using the same Hamiltonian formalism with a Hamiltonian given by the electrostatic potential in the case of drift waves and by the stream function in the case of Rossby waves. For these reasons experiments on rotating neutral fluids may serve as a means for simulating plasma drift waves. We present experimental and theoretical results on the dynamics and transport by Rossby waves. The experiments are conducted with a rotating (0-25 rad/sec) annulus of inner radius 10.8 cm and outer radius 43.2 cm. The annulus has a conical bottom to simulate the plasma density inhomogeneity, and also has input and output ports that pump fluid to generate corotating azimuthal jets (zonal flows). Fluid velocity measurements are made using particle streak photographs and hot film probes. Transport studies are done by injecting dye in the system and by tracking neutrally buoyant particles in the flow with a video camera. At low pumping rates the system develops two concentric cylindrical vortex sheets that are destabilized predominantly by the Kelvin-Helmholtz instability. At high pumping rates the waves generated at each vortex sheet merge to generate coherent Rossby type waves. Transport studies indicate that at the middle radius of the annulus, where the zonal flow gets its maximum speed, there is a very strong barrier to transport, while high mixing and transport occurs at either sides of this region. An exact solution of the CHM equation for the equilibrium (i.e. time independent axisymmetric) state is shown to agree with the measured zonal flow velocity profile. Preliminary theoretical studies on the vortex sheets instabilities are presented. To analyze the system in high pumping regime a simplified model based on linear eigenmodes of the CHM equation is proposed. Taking the stream function as a Hamiltonian we study chaotic transport in the system using the Chirikov resonance overlap criterion and an area preserving map. The results on transport obtained from the model compare well with the experimental results.

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Effect of Finite Pressure on Tearing Modes

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It was shown by Glasser et al. (1975) that in the presence of finite pressure, the stability criterion for tearing modes is $\Delta > \Delta_c$. The boundary-layer analysis which leads to this conclusion makes use of certain orderings between the equilibrium Suydam parameter D_s and the dimensionless growth rate Q. However, in the regime of high Lundquist numbers typical of existing large tokamaks, it is of interest to reconsider the predictions of the analytical dispersion equation. When we compare the predictions of the dispersion equation for zero and finite pressure, we find that finite pressure has a significant effect, reducing growth rates and introducing overstable modes, only when $Q < D_s^{2/3}$. It is known (*Greene, 1976; Rosenau, 1983*), however, that in this regime the tearing mode itself is qualitatively altered in that its growth rate scales linearly with the resistivity η (rather than $\eta^{3/5}$), which implies an effective stabilization of tearing. Hence, the stabilizing effect of Glasser et al.(1975) appears to be significant only for modes that, at zero pressure, evolve on the timescale of resistive diffusion. These conclusions are consistent with the recent numerical results of Hughes et al. (1992).

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Alfven Wave Resonance for Finite Length Field Lines*

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Finite length magnetic field lines arise in a divertor geometry, where the field lines intersect the divertor plates, and are very common in space plasma configurations such as the magnetosphere or the solar corona. The Alfven spectrum is influenced by the boundary conditions imposed at the feet of the field lines. By resonanting with the Alfven spectrum one can heat the plasma, destabilize the TAE modes, or excite micropulsations.[1] Thus, it is important to determine this spectrum.

We have worked out the problem of exciting the Alfven spectrum by driving it resonantly with a fast magnetosonic wave in a simple finite length field line configuration. The resonance condition is different from that reported by us earlier.[2] We investigate, in particular, the case of driving the Alfven spectrum (which is complex if the field is anchored in an imperfect conductor) by a real-frequency fast wave. Also discussed is the possibility of exciting ballooning modes in such a process.

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Forced Reconnection and Current Sheet Formation in Taylor's Model

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The problem of forced reconnection in a plasma which is stable to tearing modes is of considerable practical interest. In tokmaks, for instance, error-fields can induce forced reconnection in a tearing-stable plasma and produce large islands which can be disruptive. Taylor has proposed a simple model which captures the essential aspects of this problem. We revisit the treatment of Taylor's model given by Hahm and Kulsrud (1985) [hereafter, HK]. After the linear phases A, B and C, described by HK, we show that the plasma enters a nonlinear phase W with a current sheet, described by Waelbroeck (1989). The mathematical structure of this current sheet is described by an integral equation [*Rosenbluth et al., 1973*]. Due to nonlinear effects involving the phase W, the plasma does not reach the "constant - ψ" linear phase D described by HK. Instead, after the W phase, the plasma passes into the Rutherford regime. The reconnected flux at the separatrix increases monotonically from its value zero in the initial state to its asymptotic value in the Rutherford regime. Analytical expressions are given for the reconnected flux and the island width. The effect of flows is considered.

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Stability of High-n TAE Modes in the Presence of Fusion Alpha Particles

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The stability of high-n toroidicity-induced shear Alfven eigenmodes (TAE) [1] in the presence of fusion alpha particles or fast beam particles in tokamaks is investigated. The effects of alpha particles on the TAE modes are calculated perturbatively using the ideal high-n TAE solutions as the lowest order eigenmodes. A formula for the alpha particle-induced growth rate is derived using the gyro-kinetic equation in the ballooning mode representaion. Finite Larmor radius (FLR) effects and finite orbit width (FOW) effects are included for both circulating and trapped particles. We find that FLR and FOW have stabilizing effect of reducing the circulating particle response, but they also have significant destabilizing effect of broadening the particle response spectrum in the Fourier wave number space. As a consequence, the growth rate of hign-n TAE mode induced by circulating particles reaches its maximum for $k_\theta \rho_\alpha$ on order of unity. Physically, this corresponds to the condition when the distance between two resonant surfaces is on the same order of gyro-radius ρ_α. On the other hand, the trapped particle response is dominated by $\omega=\langle\omega_d\rangle$ resonance. The contribution from bounce resonances is very small. The growth rate induced by trapped particles is at maximun for value of $k_\theta \rho_\alpha$ such that $\omega=\langle\omega_d\rangle$. It is usually smaller than the growth rate induced by circulating particles. Detailed results of parameter scaling study will be presented.

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Theoretical Studies of Low Frequency Plasma Heating and Current Drive in Tokamaks.

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Theoretical and numerical studies of low frequency plasma heating and current drive in tokamaks are presented. For the regimes where fast magnetosonic waves are propagating waves, a full wave theoretical model is developed. It has the following advantages: a) the hot plasma is considered without introducing of any artificial collision frequency to resolve the plasma resonances, b) the parallel electric field of fast waves is incorporated, c) power absorbed by electrons is considered as a combination of Landau damping, TTMP, and the cross-term effect, d) fundamental and n-th harmonic ion cyclotron absorption is included, e) mode converted power is calculated, f) the resonant and non-resonant RF driven currents are considered. Attention has been paid to consideration of the following physical effects: a) poloidal and toroidal penetration of fast waves in a tokamak, and effects of ion cyclotron, and ion-ion hybrid resonances, b) effects of antenna phasing, plasma density, plasma shape, and plasma shift from the central position on the power deposition via different absorption mechanisms and antenna loading resistance, c) eigenmode excitation, d) effect of electron detrapping due to collisions on the momentum transfer current drive efficiency and bootstrap current, e) the effects of non-resonant RF driven current. The model has been applied to the Phaedrus-T and DIII-D tokamaks. The main physical results obtained are the following: all terms in electron absorption are generally important; high harmonic ion cyclotron absorption can be comparable with electron absorption and hence can be an important absorption mechanism when the ion cyclotron resonance is not in a plasma. Detrapping due to collisions is found to have a significant influence on the current drive efficiency and bootstrap current, especially when ν_e^* is not very low ($\nu_e^* \geq 0.01$). In all regimes considered the non-resonant driven current has been less than the resonant one and directed opposite. Some initial results for frequencies $\omega < \Omega_i$ will be presented as well.

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The magnetic configuration of an inductively driven, steady-state toroidal plasma,+ T. K. Chu, Princeton Plasma Physics Laboratory. We prove two theorems. The first is the theory of minimum rate of energy dissipation (for a given rate of helicity dissipation). Consider an inductively driven steady-state plasma in a volume V bounded by a surface S (or two neighboring surfaces) on which $\mathbf{B}\cdot\mathbf{n}=0$. Because the rate of change of the vector potential, $\partial\mathbf{A}/\partial t$, is constant in time and uniform in space in this plasma, its magnetic configuration is force-free: $\nabla\times\mathbf{B}=2\alpha\mathbf{B}$, where α is a constant, in time and in space. α is the ratio of the Poynting flux to the magnetic helicity flux through S. It is also the ratio of the dissipative rates of energy to helicity in V. The totality of a toroidal plasma is piecewise force-free: it consists of nested, toroidally symmetric, noninfinitesimal (by Ampere's law) regions that are separately force-free; and static equilibrium of the boundary between two adjacent force-free regions is maintained by the pressure balance across the boundary. The second theorem is the theory of maximum magnetic energy: the total stored magnetic energy in such a piece-wise force-free plasma is a maximum for a given total rate of energy dissipation (Poynting flux). A purely resistive steady state of the piecewise force-free configuration, however, cannot exist. Since neoclassical and radiative transport is slow, the removal to an outer force-free region of the unbalanced poloidal flux and pressure in an inner region, due to heating, must violate the condition $\mathbf{B}\cdot\mathbf{n}=0$ on S; the static equilibrium of the partitioning rational surfaces is ruptured, intermittently. Because of the rupture - the "relaxation", a plasma with a negative q'/q (as in reverse field pinches and spheromaks) must have the same time-averaged α in all its force-free regions; and that with a positive q'/q (as in tokamaks) has centrally peaked α's. The current distribution in a toroidal plasma also cannot attain its natural steady-state limit - a delta-function toroidal line pinch corresponding to $q_0\rightarrow 0$. The constraint that limits q_0 in a tokamak to a finite value (0.743 for a circular cross-section) is $\partial p/\partial r=0$ at $r=0$. It determines the highest allowable magnetic energy in a tokamak. It also results in sawtooth oscillations. Predictions agree with the measured F-θ diagram in RFP's and j and p profiles in tokamaks.

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Dielectric Energy versus Plasma Energy*

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Expressions for the energy content of one-dimensional electrostatic perturbations about homogeneous equilibria are revisited. The well-known dielectric energy, $\mathcal{E}_D$, is compared with the exact plasma free energy expression, $\delta^2 F$, that is conserved by the Vlasov-Poisson system‡. Since the former is written in terms of the perturbed electric field amplitude, while the latter is written in terms of a generating function, which describes perturbations of the distribution function that respect constraints of the system, the comparison requires solving the the Vlasov equation for such a perturbed distribution function in terms of the electric field. This is done for neutral modes of oscillation that occur for equilibria with stationary inflection points, and it is seen that for these special modes $\delta^2 F = \mathcal{E}_D$. In the case of stable and unstable modes it is seen that $\delta^2 F \neq \mathcal{E}_D$; in fact $\delta^2 F \equiv 0$. In the case of a general perturbation the two expressions are not equivalent; the exact energy is given by an expression proportional to $\frac{\omega |E(k,\omega)|^2 |\epsilon(k,\omega)|^2}{k^2 \epsilon_I(k,\omega)}$, where ϵ is the dielectric function and $E(k,\omega)$ is the electric field associated with a single Van Kampen mode. From this expression natural definitions of Van Kampen mode action variables and signature are obtained. The connection between this new energy expression and $\mathcal{E}_D$ is described.

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The NRL Mode and Phase-Locked Quasioptical Gyroklystron for Fusion Plasma Heating*

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The quasioptical gyrotron (QOG) is currently under development at the U. S. Naval Research Laboratory (NRL) as a high power source of millimeter-wave radiation for electron cyclotron resonance heating of fusion reactors. The QOG is widely tunable, has low ohmic heating densities at the resonator mirrors, and the inherent separation of the radiation and electron beams simplifies both radiation output coupling and the use of a depressed collector for spent electron beam energy recovery. The tunability allows for control of the position of the resonant surface in the plasma. In the basic free-running oscillator (FRO) configuration, the QOG has produced 600 kW at a frequency of 120 GHz and an efficiency of 8%, with a peak efficiency of 12% at lower power. Magnetic field tuning from 80 to 130 GHz was demonstrated, as was voltage tuning over a 3% bandwidth. The addition of a simple, single-stage depressed collector raised the peak efficiency to 16%.

A quasioptical gyroklystron configuration has recently been realized at NRL by the addition of an open-mirror prebunching resonator driven by an 85 GHz, 1.5 kW Extended Interaction Oscillator. The goals of this experiment are to demonstrate the use of the prebunching cavity to i) control the operating mode and frequency of the QOG, ii) increase the efficiency, and iii) obtain mode and phase-locked oscillator operation. The first experiments with the new set-up have demonstrated mode-primed operation in which the prebunched beam is used to selectively drive a longitudinal mode in the main resonator with higher frequency detuning than can be obtained in the FRO operating mode. The results indicate that mode priming can increase the single-mode efficiency by up to 50% and greatly enhance mode stability. Results will be presented for mode-primed operation at output powers up to 100 kW. An experiment to demonstrate phase-locked operation is currently in progress and available results will be discussed. The use of mode and phase locking opens the possibility of rapid electronic tuning at high power and efficiency.

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Two-Dimensional Numerical Simulation of Trapped Ion Mode and Drift Wave Turbulence on a Nested k-Space Grid

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A two-dimensional (2-D) k-space model is used to investigate the interaction of low-wavenumber trapped ion modes and high-wavenumber trapped electron and η_i drift wave modes in a tokamak. These simulations are the first to contain both types of turbulence simultaneously. The typical wavenumber of $0.1\,\rho_s^{-1}$ for trapped ion modes and $1.0\,\rho_s^{-1}$ for drift waves, where ρ_s is the ion gyroradius, implies that a k-space grid of at least 256×256 is required to represent the system. Since computing time scales at best linearly with the number of modes, standard simulation techniques are very expensive. A novel numerical method is used here. A series of nested grids having decreasing density extend the trapped ion mode domain into the drift wave domain. This uses a much more reasonable number of modes ($\sim$ 40 times fewer) while representing the transition from low- to high-wavenumbers in a natural way. The present work is an extension of previous studies [1,2] which separately addressed the two types of turbulence. The net direction of spectral energy transfer is a key question. The trapped electron and η_i simulations required artificial damping of the lowest modes in that system to achieve saturation suggesting a flow of energy from high to low wavenumbers. The trapped ion mode simulations did not require artificial damping of the highest modes to achieve a saturated state. This suggests that when both types of turbulence are present the trapped ion modes will be the sink of drift wave energy at low wavenumbers.

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Theory-Based Transport Simulations of TFTR L-mode Plasmas*

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Combinations of theory-based transport models[1–3] are used in the BALDUR transport code to simulate the temperature and density profiles observed in the TFTR tokamak. In an effort to make the simulations as predictive as possible, theory-based models are used for particle as well as thermal transport, and a non-equilibrium impurity radiation model is used with high-recycling boundary conditions where appropriate. Scaling with heating power, plasma current and density will be examined by comparing simulation results against experimental data. New combinations of theoretical transport models will be explored including neoclassical MHD-driven transport[4] and different models of the ion temperature gradient mode.

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An Optimum Efficiency Current Drive
for
Confining a Tokamak Plasma

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Two independent methods are used to show that electrons, as has been claimed previously [1], are indeed the carriers of the momentum of the electrostatic electron waves (electron plasma wave or electron cyclotron wave). This will lead to discovery of an electron drift in a plasma sustaining electron waves. As an application of this new physics, a method is proposed to drive toroidal current by electron waves to confine plasma in a tokamak fusion reactor. This method of current drive, in contrast to the previous methods, does not depend on auxiliary mechanisms such as Landau resonance and particle trapping for generating current. The bulk electrons which are the momentum carriers are, at the same time, the current generators. Thus the proposed method inherently posses an optimum current drive efficiency.

The physics of this method of current drive will be compared with the recently proposed method of current drive advocating particle trapping by electron waves to generate a current [2-4]. Since the electrons themselves carry all the momentum of the wave, as one might suspect, the current drive by particle trapping is perhaps the last thing to be considered for fusion application.

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NONLINEAR MHD SPECTRAL-METHOD COMPUTATION WITH SPATIALLY-VARIABLE RESISTIVITY

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Abstract

We can now claim a rather comprehensive understanding of the dynamical behavior of a voltage-driven cylinder of non-ideal magnetofluid, as long as the driving axial voltage only slightly exceeds the critical value for instability, and as long as the density and transport coefficients are spatially uniform [1]. The stability threshold is accurately calculable and a satisfactory characterization exists for the helically-distorted current channel and paired helical vortices that appear in the slightly supercritical state. Probably the biggest remaining gap between the calculations and the real-life experimental situation is that in the latter, the resistivity depends strongly upon radius. Our previous Galerkin-method code (which uses Chandrasekhar-Kendall eigenfunctions of the curl as an expansion basis) has been modified to include an arbitrarily prescribed radial resistivity profile. This makes possible an investigation of the changes in the near-threshold behavior resulting from a variable $q(r)$ safety factor. One feature of the code is that arbitrary initial MHD perturbations may be included, and no guessing or persuasion is required as to which is the "most dangerous" instability that may arise. Variable and/or tensor viscosity has not yet been included, but variable resistivity effects are now being regularly computed.

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STABILITY OF NON-AXISYMMETRIC CONFIGURATIONS OF A NON-NEUTRAL PLASMA COLUMN [1]

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A variational analysis yields sufficient conditions for the stability of a long nonneutral plasma column which obeys two-dimensional $\mathbf{E} \times \mathbf{B}$ dynamics. The column is confined by a uniform magnetic field. A boundary is aligned with the field and held at specified electrostatic potentials. When the boundary is a conducting circular cylinder, we generalize the well-known stability of a centered, axisymmetric column whose density is a monotonically decreasing function of radius. Displacement of such a column away from the axis by excitation of an $\ell = 1$ diocotron mode yields a dynamical equilibrium which is stationary in a frame rotating with the mode. This new equilibrium is shown to be stable if the column is not too large. The analysis may explain, in part, the remarkable longevity observed for $\ell = 1$ diocotron modes in experiments. The criterion also leads to a computational test for stability, which is useful when the boundary conditions are not azimuthally symmetric.

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Similarity Solutions for RMHD*

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Using the method of Lie group analysis for partial differential equations we obtain similarity solutions for reduced-magnetohydrodynamics (RMHD). From the general group of Lie point symmetries admitted by RMHD, obtained by symbolic manipulation, we look for special reductions of the number of independent variables, thus, obtaining similarity variables and in some particular cases analytic similarity solutions. The method is very general, good for linear and nonlinear p.d.e.'s, and often results in physically interesting solutions. Such similarity solutions can also be useful in checking computer codes, giving a basis for perturbation theory and describing asymptotic behavior of nonstationary flows.

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Stabilization of External kinks in Tokamaks

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External kinks pose a significant obstacle to stable operation of tokamaks. In fact the empirical β-limit, referred to as the Troyon limit,[1] was obtained by determining the threshold for kink instability with suitably optimized profiles. The salient point here is that the profiles were optimized. In an experiment such profiles are seldom achieved, consequently, many discharges do not reach the Troyon limit. This is particulary true of high-current conditions when the safety-factor, $q_{\text{edge}} \sim 3 - 4$. These latter classes of discharges very frequently terminate with a sudden disruption. It is therefore of great interest to determine techniques for stabilizing the external kink mode.

Recent initiatives in tokamak design have focussed on the possibility of operation in the second regime of stability to ballooning modes. Here too, successful stabilization of the external kink is essential.

We will present different techniques of kink mode stabilization and/or suppression. These will include the use of conducting shells, profile modification, and a new scheme for feedback stabilization.

* Supported by DoE Contract No. DE–AC02–76–CHO–3073 smallskip

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Short-Wavelength Electromagnetic Fluctuations in Edge Plasmas: Nonlinear Features

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Abstract

Nonlinear features of short-wavelength ($\rho_{Le} << 1/k_\perp << \rho_{Li}$, where ρ_{Le} (ρ_{Li}) is the electron (ion) Larmor radius) electromagnetic fluctuations in magnetically confined plasmas are studied within the context of a general renormalized statistical approach. Stationary spectra of electrostatic and magnetic field fluctuations are derived with regard to nonlinear interaction between them. The influence of finite-beta effects on stationary fluctuation spectra and anomalous electron heat conductivity are discussed. It is demonstrated that in the plasma with finite ratio between thermal and magnetic pressures the intensity of electrostatic fluctuations decreases, while the nonlinear broadening of the potential spectrum is essentially due to magnetic field fluctuations. Low-frequency (compared to the Larmor frequency) short-wavelength electromagnetic instabilities have been suggested as a possible mechanism of anomalous electron energy transport, in collisional edge plasmas in particular. Recent experimental observations give evidence of low-frequency electromagnetic fluctuations in tokamak plasma edges, characterized by broad spectra and the simultaneous presence of electrostatic and magnetic field pertubations. These basic features are incorporated in the theory presented in this report.

SELF-CONSISTENT THEORY FOR LOW-Z_a IMPURITY PELLET ABLATION IN HIGH TEMPERATURE TOKAMAKS

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Abstract

In the phenomenological model of Parks et. al.[1] for low Z_a pellet ablation, it is assumed (in contrast to hydrogen pellets) that the dynamics at the pellet's surface are as important as the hydrodynamic processes in the surrounding ablation cloud. This idea is based on the fact that the sublimation energy of low Z_a pellets is much higher than that of solid hydrogen pellets. The model was introduced for ease in fusion diagnostic sutides since universal scaling laws for the ablated state no longer apply once dissociation and ionization processes are included in the ablation dynamics.

Here, we test this phenomenological model by performing a self-consistent eigenvalue solution to the full steady-state radial ablation cloud equations. The free boundary value problem is solved when the boundary conditions for a solid-vapor phase transition[1] are satisfied. In particular, we consider both carbon and lithium pellets. Good agreement is found with the predictions of the phenomenological model, including the ablation cloud thickness.

We then consider the ablation of LiT pellets in high temperature plasmas. These pellets could fuel a D-T plasma and have considerable advantages over cryogenic DT pellets as well as in T handling. The ablation cloud equations simplified by assuming surface dissociation. We will compare the self-consistent LiT pellet results with those from the Parks et. al. model. Some comparisons will also be made using LiD pellets, as there is some experimental data on the use of LiD.

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Scaling of $\mathbf{E} \times \mathbf{B}$ Particle Diffusion in Regular and Random Hamiltonians

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The scaling of the stochastic diffusion coefficient with the potential amplitude $\tilde{\phi}$ of an electrostatic fluctuation is studied using a qualitative theory of closed and extended particle orbits for several types of periodic (four-wave) drift Hamiltonians. Depending on the type of the orbits, this theory predicts the high-amplitude scalings of diffusion, such as $D \propto \tilde{\phi}^2$ or $\tilde{\phi}^0$, thereby revealing the differences between the previously-studied models that have been in controversy.[1,2]

We also numerically study a new model of stochastic plasma transport associated with a quasi-periodic (six-wave) Hamiltonian designed to simulate a random turbulent field of a single characteristic scale. The numerical data for the Kolmogorov entropy $K \propto \tilde{\phi}^{0.56\pm0.17}$ and the turbulent diffusion scaling $D \propto \tilde{\phi}^{0.84\pm0.04}$ are obtained and compared with the percolation-theory predictions[3,4] $K_p \propto \tilde{\phi}^{0.5}$ and $D_p \propto \tilde{\phi}^{0.7}$.

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POTENTIAL AND DENSITY DISTRIBUTIONS IN INERTIAL-ELECTROSTATIC CONFINEMENT SYSTEMS*

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Inertial-Electrostatic Confinement (IEC) can be invoked in two related but complementary forms. One of these uses electron injection into a spherical geometry to provide a negative potential well, into which ions are "dropped" at low energy, with subsequent convergence to a dense central core.[1] The other uses radial convergence of energetic ions accelerated by potentials applied across concentric spherical grids to achieve a similar ion core convergence.[2] Both have the objective of creating dense ion cores by spherical radial convergence driven by ion kinetic energy.

In this process, quasi-neutrality must be preserved in order to avoid the formation of excessive variations of electrostatic potential as kinetic energy is converted into potential by the combined motion of ions and electrons in the system. Work by Hirsch[1] suggested that potential and density distributions would be formed around concentric spherical shells of alternating virtual anode and cathode structures, that would arise naturally from the interactive motion of the charged particles as governed by Poisson's equation. Such structures were also discussed in early patents by Farnsworth.[3]

In recent years a "1.5-D" Vlasov-Maxwell code (EKXL) was evolved[4] to analyze potential and particle distributions in IEC systems of the first type (e-driven). This allows and conserves transverse momentum of both species in spherically-convergent flow. Studies showed that the repetitive virtual potential structures anticipated could not form for conditions of interest in this type of IEC. We have developed a similar code (IXL) for IEC systems of the second type. Use of this has shown conditions under which these repetitive potential and density structures can be achieved. These conditions and their underlying physics will be presented and discussed, as well as their relationship to early experimental data of Hirsch and data from current work of Miley, at the Univ. of Illinois.

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Inertial-Electrostatic Confinement Studies*

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Inertial-Electrostatic Confinement is one of the earliest plasma confinement concepts, having first been suggested by P. T. Farnsworth in the 1950s. The concept involves a simple apparatus of concentric spherical electrostatic grids and intricate physics. An electrostatic structure is formed from the confluence of ion beams with a background of electrons that are provided by the grid. The desired structure consists of a concentric sequence of potential hills and valleys that may result in a concentration of ion density in a core region by virtue of the spherical geometry.

Experiments done by Hirsch[1] in the 1960s demonstrated an anomalously high (by about six orders of magnitude) production of neutrons in both D-D and D-T. Hirsch's explanation of this phenomenon was that the plasma formed a series of several concentric potential shells of opposite sign[1] that progressively trapped more density as one approached the beam focal point. However, Hirsch never directly measured the potential structure. An alternate explanation was put forward by Baxter and Stuart[2] that suggested the neutrons resulted from ion-neutral interactions. It is possible that both explanations are wrong for various reasons which will be discussed in this paper.

We have recently embarked on a combined experimental/theoretical/phenomenological program to try to shed new light on this phenomena as well as determine the suitability of IEC for fusion and other applications. The confinement scheme and our program will both be presented. Potential applications and a conceptual development path will also be discussed.

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TRANSP Analysis of Supershots with ICRF Heating in TFTR

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Strongly centralized ICRF heating may play a critical role in obtaining high Q_{D-T} and high β_α operation in TFTR as well as in future fusion reactors. ICRF heating of a dilute minority ion species leads to the formation of an energetic ion population which, according to existing theories, can act as a stabilizing agent against m = 1 internal kink instabilities which are thought to cause sawtooth oscillations in tokamak plasmas. Indeed, complete suppression of sawtooth oscillations has been observed for several energy confinement times during ICRF heating experiments on JET and TFTR. Furthermore, strong central electron heating has also been observed in these experiments, a consequence of the hot tail ions collisionally thermalizing on the bulk electrons. The corresponding rise in the central electron temperature translates into an increase in the slowing down time of either neutral beam or alpha particles, and, hence, of the density and beta of the alpha particles in the discharge. For these reasons, experiments utilizing ICRF heating of supershot plasmas are underway on TFTR. Initial results include enhancement of the neutron production rate and suppression of sawtooth activity in the high plasma current regime. The TRANSP time dependent transport code will be used in conjunction with models of ICRF wave propagation, absorption and tail formation to study the evolution of the current profile, minority distribution function and energy transport in ICRF heated supershot-like plasmas in TFTR. Comparisons will be made using pairs of similar shots which differ primarily by the presence/absence of additional ICRF heating. Changes in the local electron and ion heat diffusivities due to the additional ICRF heating will be examined. Projections of possible increases in β_α during D-T operations on TFTR will be discussed.

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Neoclassical Diffusion in a Turbulent Plasma*

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A new approach to plasma transport is described where the toroidal drift is considered as a perturbation to the motion of particles in electromagnetic oscillations, $u_d \ll \tilde{v}$. Such a condition typically corresponds to the fluctuation levels observed in tokamak experiments. From the analysis of particle trajectories it is shown that there is a small group of particles that move in the direction of toroidal drift, even if $u_d \ll \tilde{v}$, and due to which several neoclassical phenomena should persist at high fluctuation levels. This small group of particles also plays a major role in anomalous transport processes. Percolation theory is used to determine the scaling of the diffusion coefficient, D. This coefficient is weakly dependent on fluctuation's spectrum and is higher than the neoclassical plateau coefficient, $D^{p\ell}$, in both banana and plateau regimes:

$$D \sim D^{p\ell} \left(\frac{\tilde{v}}{u_d} \right)^{4/7} \gg D^{p\ell} \, .$$

Numerical simulation results support the theoretical scaling arguments.

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A UNIFIED THEORY OF TOKAMAKS AND STELLARATORS

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High performance computer codes have been developed to study equilibrium, stability and transport in tokamaks and stellarators with an emphasis on three-dimensional asymmetry. Bifurcated equilibria without axial symmetry are advanced as a mathematical model appropriate for the prediction of transport in tokamaks. Anomalous transport of electrons is explained as the effect of trapping in the wells and hills of the relatively small parallel component of an electrostatic field determined by quasineutrality. Conservation of momentum should not in general be expected to produce quasineutrality. Calculations have been performed to assess the merits of a standard configuration for ITER. The results are compared with the optimized design of a stellarator obtained by adding an $m=2$, $n=1$ sideband to a Heliac of large aspect ratio to reduce three-dimensional effects.

Computer Simulation of Transport Driven Current in Tokamaks*

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Plasma transport phenomena can drive large currents parallel to an externally applied magnetic field. The bootstrap current theory accounts for the effect of banana diffusion on toroidal current, but the effect is not confined to that transport regime, or even to toroidal geometry. Our 2½–D, electromagnetic, particle simulations have demonstrated that Maxwellian plasmas in static toroidal and vertical fields spontaneously develop significant toroidal current, even in the absence of the "seed current" which the bootstrap theory requires.

Other simulations, in both cylindrical and toroidal geometries, and without any externally imposed electric field, show that if the plasma column is centrally fueled, and if the particle diffusion coefficient exceeds the magnetic diffusion coefficient (as is true in most tokamaks) then an initial toroidal current grows steadily, apparently due to a dynamo effect. When the plasma is fueled at the edge rather than the center, the effect is greatly diminished, but central fueling is probably needed in a reactor for particle control reasons. Our simulations indicate that such fueling, coupled with the central heating due to fusion reactions may drive all of the tokamak's toroidal current.

The bootstrap and dynamo mechanisms do not drive toroidal current where the poloidal magnetic field is zero, and so the bootstrap theory asserts that a "seed current" must be maintained by some other means at the magnetic axis. Our simulations, as well as initial theoretical work, indicate that in tokamak conditions, a combination of binary collisions and $\vec{E} \times \vec{B}$ vortex motion transport current from the outer regions of the plasma to the magnetic axis, by a process which can be modeled as an effective electron viscosity. If this self-seeding mechanism functions in experiments as it does in our simulations, then transport driven current would eliminate the need for any external current drive in tokamaks, except simple ohmic heating for initial generation of the plasma.

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ENERGY AND CURRENT TRANSPORT: SYMMETRY BREAKING AND DEGRADATION

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The effective transport of the electron thermal energy and that of the longitudinal current density are assumed to be interdependent and described by a common diffusion matrix equation. The transport matrix is taken to be symmetrical[1] when the applied electric field E is responsible both for driving the current and for heating the plasma. The transport coefficients that appear in the matrix equation are an electron thermal conductivity κ_e and a "thermo-viscous" coefficient L that are of non-collisional origin. The latter coefficient describes the energy and current transport arising from the combined gradients of the electron temperature T and current density J. The thermo-viscous coefficient is connected with a thermal energy inflow[2] when the relative temperature gradient becomes smaller, by an appropriate factor, than the current density relative gradient.

We interpret the energy degradation that occurs when the externally injected heating is dominant over Ohmic heating in terms of the breaking of the symmetry of the transport equations. This leads us to introduce a change in the relationship between the electron temperature and the current density profiles, and a non-linear dependence of the electron heat flow on the temperature gradient. The resulting enhancement of the effective thermal conductivity can account for the observed degradation of the energy transport. In particular, in the limit where Ohmic heating is negligible, we write the coupled transport equations as

$$P_{inj} = -\nabla \cdot \left[\left(\kappa_e + \frac{9}{4}\frac{LJ^2 f^2}{T} \right) \nabla T - \frac{1+3f}{2} L \left(\nabla J - \frac{3(1-f)}{2}\frac{J}{T}\nabla T \right) \right]$$

$$E - \eta J = -\nabla \cdot \left[L \left(\nabla J - \frac{3(1-f)}{2}\frac{J}{T}\nabla T \right) \right],$$

where P_{inj} is the externally injected power, η is the collisional resistivity, f is a function of the gradients that drive the modes producing L, and $\kappa_e + (9/4)LJ^2f^2/T$ is the total thermal conductivity. This new thermal conductivity represents the degradation of the energy confinement caused by the loss of the symmetry of the transport equation, whereas the term proportional to the profile combination $[\nabla J - (3/2)(1-f)(J/T)\nabla T]$ corresponds to the energy inflow[2] ("heat pinch").

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The Ballooning Instability in Vortex Rings with Swirl*

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Vortex rings in classical fluids have a topology similar to the tokamak. Like the tokamak, they are subject to the ballooning instability which develops along streamlines (rather than magnetic field lines). In contrast to the plasma case where unstable ballooning modes have a fixed spatial structure and grow exponentially in time, ballooning modes in fluids may grow either exponentially (in a Floquet-type manner) or algebraically.[1]

We have derived a particularly simple necessary and sufficient stability criterion for the algebraically growing modes. Like the Mercier criterion, it has the form of an algebraic inequality which involves surface averages of quantities related to components of the streamline curvature. It implies, for example, that vortex rings without swirl having convex streamlines require that the Bernoulli function be monotonically increasing outwards (as in the classical Rayleigh criterion for cylindrical flows). The straight (columnar) case was discussed in detail. One interesting result is that, typically, the flow is unstable unless the axial velocity is uniform.

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ACTIVE CONTROL OF FLUCTUATIONS IN A REVERSED-FIELD-PINCH

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Recently, feedback control has been effectively used to increasing the disruptive density limit in a tokamak[1]. It does so by reducing the saturated $m = 2$, $n = 1$ instability. The RFP, in contrast, do not disrupt. Its instabilities self-stabilize via the dynamo, which enhances shear, and via nonlinear coupling with small scale dissipative modes. Nevertheless, feedback control of fluctuations is of potential import to the RFP since it may reduce thermal transport along stochastic magnetic field lines[2].

Technically, RFP instabilities are more complicated to control than tokamaks: multiple modes are unstable; they are resonant at different locations; and they interact with each other. Among them, the most difficult modes to control, and probably the most important[3,4], are ones that resonate near the axis and the internal kinks. They are particularly prone to the phase-flip instability where the feedback coils actively enhance the instability when proper phase relation between the instability and the coil signals is not maintained. This is because it is both more difficult to sense and to control plasma motion far from the boundary, especially since the transmission properties of the edge plasma must be considered.

Using numerical MHD simulation, we have tested a relatively practical scheme (one that does not rely on sensing the perturbed field inside the plasma) that reduces the energy of the dominant instabilities by a minimum of 30% when the modes are considered individually. When multiple modes are present, however, their interaction creates more dynamic modal behavior which can defeat the feedback scheme. These results, the occurrence of the phase-flip instability, and possible new feedback schemes will be discussed in more detail.

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Kinetic Toroidal η_i-mode Study in the Presence of Parallel Sheared Flow*

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The gyrokinetic integral equations for the study of ion temperature gradient mode in toroidal geometry are extended to include an equilibrium ion parallel sheared flow $v_{\parallel}(x)$. Magnetic gradient and curvature drifts of the ions as well as finite ion Larmor radius effects are included. Unlike the poloidal sheared flow[1] which is principally stabilizing mechanism for $L_s V'_E/c_s > 1\text{-}2$ on the η_i-mode, the toroidal sheared flow is destabilizing. Besides the effect of the flow shear which appears in slab model, the flow speed has some independent effects on the mode due to the toroidicity of the system. Systematic numerical results from local and non-local equations will be presented in the electrostatic approximation. The possibility for the treatment of poloidal sheared flow in this approach will be discussed and preliminary results will be presented.

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MODIFICATION OF THE PREISCHE PEST POST-PROCESSOR

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A new post-processor for the MHD Tokamak Stability Code PEST[1] was recently developed.[2,3] The PEST code provides Fourier decompositions of the components of the eigenfunctions which are in non-orthogonal directions and not properly normalized;

$$\boldsymbol{\xi} = \frac{\mathcal{J}\xi_\psi^P}{R^2 g B_0}\nabla\theta \times \boldsymbol{B} + \frac{i\mathcal{J}\xi_s^P}{R^2 g B_0}\boldsymbol{B} \times \nabla\psi + \frac{i\xi_B^P}{B_0}\boldsymbol{B}$$

with $\mathcal{J}$ the Jacobian and RB_0g the toroidal field at the radius R. Thus, these eigenfunctions do not give a true indication of the nature of an unstable displacement. Preische provided tools for obtaining properly normalized components of $\boldsymbol{\xi}$ in the orthogonal directions,

$$\boldsymbol{\xi} = \xi_\psi \frac{\nabla\psi}{|\nabla\psi|} + \xi_s \frac{\boldsymbol{B} \times \nabla\psi}{|B||\nabla\psi|} + \xi_B \frac{\boldsymbol{B}}{|B|},$$

and extended the analysis to get $\nabla\cdot\boldsymbol{\xi}$ and some components of the perturbed magnetic field $\boldsymbol{Q}$. We have continued her work to include Q_ψ, Q_s, Q_B, Q_R, Q_Z, and Q_ϕ, as well as the perturbed pressure δp. The program is being made interactive to permit the choice of quantities to be displayed. The code will also provide the perturbed field at points outside the plasma. This should facilitate comparison of PEST code predictions with experimental data. The status of the work and an illustration of its capability will be presented.

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Low-Frequency Plasma Motion: Energy Conservation Law

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Abstract

It is shown that the basic description of low-frequency quasi-flute plasma motions within the context of renormalized plasma electrodynamics yields an energy conservation law exact with respect to nonlinearity. The energy density is proved to be a quadratic functional of the electric field strength for an arbitrary regime of nonlinear interaction (either weak or strong). Nonlinear equilibrium spectrum of low-frequency oscillations with regard to finite-Larmor-radius effects is obtained. Reduced energy conservation law is derived and analysed within the context of general microscopic description, and the correspondence to the gyrokinetic models is discussed.

Turbulent Transport across a Separatrix due to ETG Driven Instability in Tokamak SOL

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Understanding the transport properties of the edge plasma across a magnetic separatrix is essential for any magnetic confinement device. The electron-temperature-gradient driven instability can be excited in tokamak scrape-off-layer[1,2]. This instability penetrating into core plasma can provide a new candidate to cause edge tokamak fluctuation and anomolous radial transport. We have formulated a linear theory that is applicable for handling two regions either side of the separatrix in a shearless slab, with matching conditions at the separatrix. The mode potential is found to peak at the separatrix, and propagate and decay toward both core and SOL region, on the radial scale length $\Delta x < 1/k_y$ depending on the parallel wave length. Renormalized one-point analysis of the two-field (ϕ and T_e) Hasegawa-Wakatani-like model in SOL has been developed for flute modes in the electrostatic and cold ion limits. The set of equations resembles Hasegawa-Wakatani equations for a shearless slab used to describe drift wave turbulence, however, we use different parallel electron dynamics due to the sheath boundary condition adjacent to the divertor plates. Since $k_\perp \rho_i \ll 1$ and $\omega \leq \omega_{*T_e}$ for the instability, the $\mathbf{E} \times \mathbf{B}$ convection of temperature nonlinearity dominates over the $\mathbf{E} \times \mathbf{B}$ convection of vorticity nonlinearity. The implication for saturation levels and transport will be discussed. Secondly, since in the presence of the separatrix, the mode characteristics are different in the core and SOL. Nonlinear coupling between the core and SOL is possible, and will be explored. Effect of neutral particle ionization will be considered.

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Generation of a Minimum Enstrophy Flow in the Tokamak Scrapeoff Layer

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Turbulence in the scrapeoff layer of a tokamak (SOL) can be of interest both for practical reasons, and as a paradigm of magnetic plasma turbulence which can be well diagnosed. Recent theoretical studies[1,2] have revealed a robust instability that can arise in the SOL. This instability, with drift wave ordering, is driven by an electron temperature gradient in the presence of limiter-tied field lines. Nonlinearly, the system of equations is similar to the two-field drift wave model studied by Gang *et al.*[3] Specifically, it can be shown that a dual cascade occurs in which enstrophy cascades to short scale, and kinetic energy inverse cascades to large scales.

The present work addresses the nonlinear dynamics and transport of this instability. First, we argue that the usual diffusive model of turbulent transport is inapplicable in the presence of the inverse cascade: the necessary separation of scales between the fluctuations and the equilibrium is violated when the inverse cascading energy approaches the scale sizes of the equilibrium. Instead, the net effect of the turbulence is to form a minimum enstrophy equilibrium, which can be predicted by a variational calculation (holding the kinetic energy fixed). This approach circumvents the usual transport coefficients, since it gives the entire set of profiles. The result depends on the details of the instability only through a single number: the amplitude of the resulting flow, which is determined from the balance of turbulent drive with viscous damping. This approach can accomodate a wide variety of SOL destabilization mechanisms; the primary condition is that the nonlinear interaction conserve both enstrophy and kinetic energy.

The minimum enstrophy flow exhibits several properties suggestive of the flows present in H-modes. Among other things, it has a poloidal shear flow similar to that found in tokamak edge regions. The velocity profile is peaked at the separatrix, and penetrates into the plasma when magnetic pumping can be suppressed. Furthermore, since the equilibrium is the result of a minimization principle, the flow exhibits a high degree of stability.

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A Hybrid Particle-Fluid Simulation for Model Tokamak Plasma Edge Turbulence

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Increasing evidence that the edge plasma plays a crucial role in global tokamak confinement and a new discovery that a drift wave type instability can be driven by the electron temperature gradient in tokamak scrapeoff-layers[1,2] motivate this study of 3-dimensional (x, y and z) hybrid particle-fluid simulation of anomalous transport in the edge plasma region. The simultion model consists of fluid ions and drift kinetic electrons in a shearless slab with two divertor plates intercepting the magnetic field that is applicable for two regions separated by a fake magnetic separatrix, periodic regions along magnetic field inside the separatrix and finite length along the magnetic field outside with a model logical sheath boundary conditions. The evolution of ions is determined by a set of fluid equations for vorticity $\nabla_\perp^2 \phi$, ion parallel momentum and ion temperature. The code is capable of simulating electron temperature gradient driven turbulence in SOL, ionization-driven drift wave turbulence in the edge plasma[3], nonlinear coupling between the core and SOL across a magnetic separatrix, and the resulting anomalous transport. Current investigations focus on the physics issues of linear instabilities and nonlinear evolution of the modes in cold ion limit.

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Confinement Enhancement in Multiple-Mirror Systems by Transient Potential Barriers*

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Open-ended confinement systems operating at high plasma density would be attractive as fusion power systems provided means can be found to minimize end losses. Multiple-mirror systems that have been studied in the past for this purpose require highly collisional plasma conditions (very high density, low plasma temperature) to achieve effective confinement [1]. Post and Li [2] have shown that confinement time in multiple-mirror systems can be enhanced over the usual (linear) result by a factor that is exponential in the number of cells if the cell-to-cell escape probabilities can be preferentially biased toward the central confinement cell. If an effective means could be found to introduce such biases the practicality of high-density linear systems for fusion power applications would be substantially enhanced.

This paper explores the use of multiple, transient, time-correlated, potential barriers to achieve directionally biased loss probabilities. One method to create localized transient potentials is to use fast-pulsed mirror coils as employed in the Mirrortron [3,4]. An alternative method would be to employ high-power microwave beams incident on regions of the plasma where there exists a magnetic gradient [5]. In either case the potentials are generated by taking advantage of the difference in response between electrons and ions when subjected to transient $\mu\nabla B$ forces.

The mechanisms by which the potentials are generated will be discussed and the results from a 1-D computer code simulating the loss processes will be presented.

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ENERGY CASCADES FOR DRIFT TURBULENCE WITH TRAPPED IONS*

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The nonlinear theory of drift turbulence in the presence of magnetically trapped ions is reexamined. We derive a generalised fluid model that embraces the two physically important limits of Hasegawa-Mima (HM) response (hydrodynamic circulating ions) and the dissipative trapped ion mode response (adiabatic circulating ions), coupling them by a simple parallel ion dynamics. Whereas the conventional HM (small $k_{||}$) limit predicts an *inverse* cascade of energy from short to long scales due to the inviscid conservation of both energy and enstrophy, it has recently been stressed[1] that the trapped ion mode limit (large $k_{||}$) leads to a *direct* energy cascade from long to short scales. In the presence of *both* types of responses, the nature of the cascade is strongly modified for intermediate values of $k_{||}$. The statistical dynamics of this three-field model is studied using a Markovian statistical closure scheme. The analysis is done by first computing the modified turbulent spectra for both limits in the presence of parallel ion dynamics. The dynamics of the intermediate scales is then estimated from these results. We discuss possible cascade scenarios based on cascade rates of this composite model. The results are compared with the time asymptotic turbulent spectra derived using quadratic invariants of the system.

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Model Studies of L-H Transition Dynamics with Turbulently Generated Differentially Rotating Flow

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The L-H transition is frequently depicted as a two-step process wherein a mechanism independent of collective oscillations generates a sheared poloidal flow, which in turn modifies the ambient turbulence. Here we explore the possibility of a transition process with a single step consisting of spontaneous generation of differentially rotating flow by turbulent fluctuations whose amplitude and structure simultaneously adjust to the self-generated flow.

The fluctuations are described by a simple dissipative trapped electron model. Because measured flows appear to have a flow curvature that is as large as the flow shear, the effects of both shear and curvature are incorporated. The saturated state includes mode structure modifications due to shear and curvature and the moderating effects of spatial nonuniformity of the turbulent diffusivity. The generation of shear flow and flow curvature is described by the appropriate momentum balance equations or equivalently, as a transport process driven by the turbulent Reynolds stress. Shear flow is induced by the Reynolds stress when radially outward momentum transport is modified by an eigenmode asymmetry. Curvature is driven by diamagnetic rotation. These processes are off-diagonal in the transport matrix. A diagonal element corresponding to turbulent viscosity enters through the term associated with Kelvin-Helmholtz driving but is intrinsically weak for dissipative trapped electron modes.

Approximate solution of the coupled equations for the saturated fluctuations and turbulently generated flow shear and curvature exhibits an accessibility condition for steady state turbulently generated flow that is linked to the edge temperature. This condition reflects the balance between magnetic pumping and flow generation via the amplitude dependent Reynolds stress required for a steady state flow. If the fluctuation level required to balance magnetic pumping is higher than the saturated level, no steady state flow is possible. Above an edge temperature threshold, the magnetic pumping is sufficiently decreased for the amplitude dependent Reynolds stress source to balance collisional momentum dissipation, at a finite level of turbulently generated flow.

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The Exact and Drift Hamiltonian

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Abstract--A canonical Hamiltonian treatment for the motion of the guiding center of a charged particle in a magnetic field of a toroidal configuration is given. The Hamiltonian of the exact trajectory, first and second order corrections to the standard drift Hamiltonian are given in the Boozer coordinates for vacuum magnetic field with magnetic surfaces. The exact Hamiltonian depends on both the field strength and the shape of the magnetic surfaces (the metric of the magnetic coordinates) while the standard drift Hamiltonian depends only on the field strength. The first order correction, in gyroradius to system size, to the standard drift Hamiltonian depends in a generic way on the metric of the magnetic coordinates, as does the exact Hamiltonian.

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Bootstrap Currents in Tokamaks of Arbitrary Aspect Ratio

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A theoretically based empirical formula for the bootstrap current in tokamaks of arbitrary aspect ratio is presented. This expression is evaluated by fitting to many numerical calculations of the bootstrap current (where the required flux surface averages have been derived using a self-consistent equilibrium) and is valid over a wide range of tokamak relevant parameters and plasma profiles. In particular it should be useful for obtaining good, quick estimates of the bootstrap current fraction in present tokamaks (e.g. JET, TFTR, etc.) as well as in future generation machines such as ITER.

The START device at Culham Laboratory (with an aspect ratio of 1.5 or less) is a case when such neoclassical effects might be expected to become important. Recent measurements of high electron temperatures in START provide strong evidence for enhanced resistivity which indicates that neoclassical effects are indeed playing a role. It is intended to verify this through an accurate measurement of the loop voltage and this provides the motivation for the remainder of this paper in which the potential of using this technique to identify the neoclassical resistivity and bootstrap current in START is considered. Equilibria are generated using a neoclassical current profile and parameters which are typical of the START device. The two modifications to the loop voltage which are considered are the increase which is expected due to the enhanced resistivity caused by trapped electrons and the decrease which is expected as a result of the bootstrap current. The bootstrap current contribution is negligible at low β_p and there is a significant (more than a factor of two) difference between the classical and neoclassical predictions for the loop voltage. At higher β_p the bootstrap current fraction becomes significant (contributing approximately one third of the total current for $\beta_p \sim 1$) and it becomes difficult to differentiate between the classical and neoclassical predictions for the loop voltage. This result suggests that measurement of the loop voltage at low β_p may be a good method for testing neoclassical resistivity, which then enables the bootstrap current fraction to be determined through loop voltage measurements at high β_p.

THREE-DIMENSIONAL FLUID SIMULATION OF EDGE TURBULENCE IN TOKAMAKS[1]

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A three dimensional code developed for the study of resistive ballooning modes in the edge region of tokamaks has been used to investigate the generation of the self-consistent shear flow by the Reynolds Stress as well as the Anomalous Stringer spin up caused by the geodesic curvature. These modes are found to give rise to anomalous particle transport which is strongly poloidally asymmetric since the modes have a significant ballooning character. We will present results which will compare the two flow generation mechanisms. Also we will discuss circumstances under which the self-consistently generated shear flow can completely stabilize the turbulence and those when the shear flow can co-exist with the turbulent fluctuations. The relevance of these studies to experiments will also be addressed.

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Bohr-Sommerfeld Eigenfrequencies and Eigenfunctions for Vector Wave Equations†

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The Bohr-Sommerfeld rules for determining the eigenfrequencies and eigenfunctions for scalar wave equations are familiar. (A scalar wave equation describes a wave field with a single component.) In one dimension, the rules state that the ray supporting an eigenfunction forms a closed loop in the x-k ray phase space, such that the x-k area enclosed (the action of the loop) is equal to $2\pi(n+\frac{1}{2})$. In higher dimensions, the rules apply in the case that the ray dynamics is integrable, or at least possesses invariant tori of the KAM type. In this case, the tori supporting eigenfunctions are those whose action integrals around the topologically distinct closed contours on the torus are either integer or half-integer multiples of 2π. These rules date back to the old quantum theory, and are now well understood.

For vector wave equations, however, the asymptotic theory for computing eigenfrequencies and eigenfunctions has only recently been brought into satisfactory form. There has existed for some time a WKB theory for general vector wave equations, due to Bernstein[1]; this theory allows one to solve initial value problems by ray tracing. It does not, however, produce an easy generalization of the Bohr-Sommerfeld quantization rules to vector wave equations. After studies[2,3] on the one-dimensional case, the correct quantization rule in any number of dimensions was stated by Kuratsuji and Iida,[4] based on a path integral approach with an incorporation of Berry's phase. Many aspects of the problem were left incomplete by Kuratsuji and Iida, however, and we have recently[5] filled in the missing elements from the standpoint of WKB theory.

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Two Dimensional Aspects of Toroidal Drift Waves in the Ballooning Representations*

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By systematically doing the higher order theory, the predictions of the conventional ballooning theory (CBT) are examined for non-ideal systems. For the complex solvability conditions to be satisfied, radial variations of the lowest order mode amplitude needs to be invoked. It turns out, however, that even this procedure with its concomitant modifications of eigenvalues and eigenstructures, is not sufficient to justify the predictions of many CBT solutions; only a small set of the CBT solutions could be put on a firm footing. To demonstrate our general conclusions, theoretical and numerical results are presented for systems of fluid drift waves with nonadiabatic electrons response.

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APPROXIMATE MODEL OF DTEM WITH ION LANDAU DAMPING AND FLR EFFECTS*

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Dissipative trapped electron modes (DTEM) may be a cause of deteriorated confinement in tokamaks and stellarators. Here we present an approximate model to study DTEM that includes ion Landau damping and finite Larmor radius effects in slab geometry. We also present comparisons of a number of approximations and exact solutions for the local dispersion relation. In the accompanying paper, numerical, radially resolved calculations are discussed for similar levels of approximation.

The model follows from the gyro-kinetic equation.[1] The Landau fluid approximate techniques are those developed systematically by Hedrick and Leboeuf[2−5] as an extension of the early work by Hammett and Perkins[6] on ion temperature gradient modes. Comparison of solutions to the local dispersion relation are given for 1, 2, 3, 4, and 5 pole approximations, as well as the full plasma dispersion function. Higher order Pade approximations are given for $\Gamma_0(b) = I_0(b)e^{-b}$ and compared to the original Pade approximation of Hsu and Hazeltine[7] and to several other commonly used approximations as well as the exact function. Pseudo-potentials for all these approximations are developed to facilitate comparison, using shooting techniques, of radially resolved linear calculations. Evolution equations, which closely resemble those used in standard reduced MHD,[8] are presented since these are better suited to non-linear calculations.

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Reduced Microscopic Description of Magnetized Plasma

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Abstract

A general microscopic theory is elaborated for the description of low-frequency (compared to the Larmor frequency) processes in magnetized plasma. Reduced microscopic equations, which govern slow plasma motions, are derived from the Klimontovich equation for the microscopic particle distribution and the microscopic field equations. The theory involves self-consistently the information on a velocity-gyroangle dependence. No gyroangle averaging is used. The particle distribution function provides incomplete information on gyroangle dependence in the form of a probability distribution as a result of closure. The theory is developed up to arbitrary orders in a small parameter. It is demonstrated that the gyrokinetic models do not take into account finite-Larmor-radius effects correctly.

Filamentary Construct of High-Beta Plasmas*

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Increased evidence in observation in astrophysics and in laboratory plasmas points to the tendency of high-β plasmas to form filamentary structures. The most striking example of this may be the solar chromosphere, but observational examples are not limited to this. This may be regarded as a manifestation of more general evolution of nonlinear fields, including turbulent hydrodynamics. With a very large order parameter (such as the Reynolds number and the Lunquist number) the fluid tends to form filamentary or highly intermittent structures. In place of the conventional harmonic functions some have tried to implement vortical functions in hydrodynamics[1] and in guiding center plasmas[2]. Here we suggest the two-color vortical construct of MHD system for high-β plasmas, based on the Elsasser variables. We obtained two dimensional and three dimensional energy spectra in thermodynamical equilibrium under the present representation, which differ from the conventional equipartitian thermodynamical equilibrium. The notable phenomena include possible phase transition and spontaneous structure formation in these MHD plasmas. We have developed computational codes for the above, showing some preliminary evidence to support our above contention. Such discrepancy in two different thermodynamical spectra may arise from the deep root of the nonlinear field theory itself.

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Painlevé Analysis of Particle Dynamics in Magnetic and Electric Fields Associated with Reconnection

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For a plasma in the collisionless régime, test-particle modelling can lend some insight into the macroscopic behavior of the plasma, e.g conductivity and heating. A common example for which this technique is used is a system with electric and magnetic fields given by

$$\mathbf{B} = \delta\, y\, \hat{\mathbf{x}} + x\, \hat{\mathbf{y}} + \gamma\, \hat{\mathbf{z}}, \quad \mathbf{E} = \epsilon\, \hat{\mathbf{z}}, \tag{1}$$

where δ, γ, and ϵ are constant parameters. This model can be used to model plasma behavior near neutral lines* ($\gamma = 0$), as well as current sheets† ($\gamma = 0$, $\delta = 0$).

The integrability properties of the particle motion associated with (1) might affect the plasma's macroscopic behavior, and it is only natural to ask the question *"For what values of δ, γ, and ϵ is the system integrable?"* To answer this question, we have employed *Painlevé singularity analysis*, which is an examination of the singularity properties of a test particle's equations of motion in the complex time plane. This analysis has identified two field geometries for which the system's particle dynamics are integrable: the circular O-point case and the case of the slab. The singularity property tests also identified a large, dense set of field geometries that may yield dynamics that are at least partially integrable. Particle trajectories, existence of integrals of the motion and a discussion of the reliability of Painlevé analysis as a diagnostic for the presence of chaotic scattering‡ will be presented.

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POLOIDAL ROTATION AND DENSITY ASYMMETRIES IN A TOKAMAK PLASMA WITH STRONG TOROIDAL ROTATION

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Poloidal rotation and poloidal density asymmetries have received increased attention recently because of their apparent linkage to confinement properties.

We consider tokamak plasmas with strong, unbalanced NBI. Two notable characteristics have been observed in such plasmas: 1) $v_\phi/v_{th} \sim O(1)$ for ions, implying $E/B_\theta \sim O(1)$; and 2) anomalously large radial aprticle fluxes, which exert a torque to drive poloidal rotation. Our approach is to take the observed values of toroidal rotation and radial particle flux as given, then to work out the implications, via particle and momentum balance, for the poloidal rotation and poloidal density asymmetries, which are coupled thereby.

Poloidal rotation and poloidal density asymmetries at r/a = 0.5 have been calculated for main (deuterium) and impurity (carbon) ions in a two-species specialization of the model. The predicted poloidal rotation is negative (B_θ direction), different for carbon and deuterium, and in the range $0.1 \lesssim (|v_{\theta j}|/v_{thj})/(B/B_\theta) \lesssim 0.4$ for parameters characterizing present tokamaks. The poloidal rotation generally increases with increasing toroidal rotation, decreases with increasing radial deuterium flux, and varies non-monotonically with collisionality. In-out poloidal density asymmetries vary from $\sim 0.1\,\epsilon$ to $\sim 1.0\,\epsilon$ for carbon (and about half of this magnitude for deuterium) as the carbon toroidal rotation speed increases from $\sim 0.2\, v_{thI}$ to $\sim 0.7\, v_{thI}$, independent of collisionality or radial deuterium flux. Up-down poloidal density asymmetries vary from ~ 0.0 to $\sim 0.4\epsilon$ for carbon (and half this for deuterium) over the same range of carbon rotation speeds, for $\nu^*_{II} = 0.5$, and are quite sensitive to collisionality and radial deuterium flux.

The effective composite poloidal asymmetry factor of the gyroviscous theory for momentum transport was evaluated using the results of poloidal rotation and poloidal density asymmetry calculations. This factor increases with increasing toroidal rotation and has a complex dependence on both collisionality and the radial deuterium flux. The calculations broadly support the values of the composite effective poloidal asymmetry factor that have been assumed in the successful comparisons of the gyroviscous theory with experimental momentum confinement properties.

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Gyro-Landau Fluid Model Simulations of Ion Temperature Gradient Mode Turbulence in Toroidal Geometry

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Fluid models have found wide use in simulating plasma turbulence because of their numerical simplicity and tractability. Such models time advance a few velocity moments of a kinetic equation rather than the velocity distribution function. Until the recent work of Hammett and Perkins [1], it was not appreciated that a fluid moment hierarchy could be truncated by the addition of a collisionless heat diffusivity [$\chi = (2\sqrt{\pi})\, v_{\rm th}/k_{\parallel}$] to accurately represent the kinetic effects of Landau damping. Taking moments of the nonlinear electrostatic gyro-kinetic equation, we have generalized this earlier $E \times B$ and parallel motion result to include large gyro-motion and, in particular, the curvature drift motion and resonance effect. Nonlinear $E \times B$ equations of motion for perturbed gyro-density, parallel velocity, and parallel and perpendicular pressures result. A highly constrained procedure is developed for truncating the higher moments in terms of the lower by modeling the deviation from a perturbed Maxwellian (with reactive as well as dissipative elements) to fit the kinetic linear response for both small and large values of the kinetic parameters for parallel, gyro- and curvature motion: $k_{\parallel}v_{\rm th}/\omega$, $(k_{\perp}\rho)^2/2$, and $\omega_{\rm D}/\omega$. Taking adiabatic electrons, various gyro-landau fluid (GLF) models for the ions are tested for ion temperature gradient (ITG) mode linear local (constant k_{11} and $\omega_{\rm D}$) stability against the kinetic theory. A GLF model is then applied in a 3 D (m, n, r) nonlinear code to simulate ITG mode turbulence in tokamak sheared toroidal geometry. The transport is found to be considerably larger for tokamak geometry as compared to "sheared slab" geometry (*i.e.*, curvature terms turned off). Scaling with respect to $\eta_{\rm i}$ and q is studied. Applied shear in the radial electric field is found to shut down the transport just beyond the linear stability point. The code operates on the CRAY and the CONNECTION MACHINE (CM). It is expected that large grid studies on the CM will allow scaling with respect to gyroradius to be studied.

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Fast Ion Driven Ion Bernstein Instabilities via Relativistic Mass Variation*

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Inclusion of relativistic mass variation for the fast ions' cyclotron motion is essential for a proper kinetic calculation of the electrostatic wave/particle interaction. This is true even for mildly relativistic ions. The effect contributes a new term in the dispersion relation which can destablize the system. The most unstable modes turn out to be ion Bernstein waves which propagate perpendicular to the axial magnetic field in a homogeneous plasma. The instabilities have a broad wavelength spectrum with significant growth rates (e.g., ~1% of the ion cyclotron frequency) and persist for higher harmonic Bernstein waves. Typical wavelength is of the order of fast ions gyroradius. The fast ions can be isotropic, or low density as in dilute fusion products (e.g., protons from D-D or α particles from D-T reactions) and/or produced by neutral beam injection. This mechanism can slow down fast ions and heat the background plasma. It may also provide a means for harmonic ion heating. Since the wave electric field and the perturbed density fluctuations are perpendicular, they may collectively cause plasma transport across magnetic field. We believe that this may provide an explanation for recent JET experimental results on observed superthermal in cyclotron emission. For tokamak parameters, it is more likely to be unstable in the edge regime than in the center.

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Calculations of Combined LH, FW, and EC Power Deposition and Current Drive

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The CQL3D relativistic bounce-averaged Fokker-Planck code [1] has been improved by incorporating a *unified* treatment of rf quasilinear diffusion due to wave-particle interactions at all cyclotron harmonics, including the zeroth harmonic. Wave characteristics (frequency, position, wave number, polarization, and normalized energy flux) are passed to CQL3D, corresponding to rf wave increments which are obtained with an external ray tracing or full wave code; CQL3D calculates the self-consistent distribution functions $f\ (v_0,\ \theta_0,\ \rho)$ and wave damping associated with the wave increment. Here, v_0 is a momentum per mass, θ_0 is pitch angle evaluated at the minimum magnetic field point on a flux surface, and ρ is a radial coordinate. The calculations has been extended to simulation of multiple modes of wave energy. We describe computational specifics of the quasilinear diffusion coefficient calculation, and the damping. Applications are made to the combined fast wave and lower hybrid heating and current drive experiments on JET [2]; EC, LH, and fast wave in DIII–D, individually and in combination with each other; and ECCD in ITER.

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1D and 2D Code-Merging with Applications to a Self-Consistent Core-Edge Plasma Simulation

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ABSTRACT

A new approach for complex simulation on multiple space and time scales of plasma experiments has been recently proposed [1] as related to the Numerical Tokamak eXperiment (NTX) concept.
Two or more codes run at the same time while simulating different plasma regions, eventually with different number of dimensions, and on different time scales. The codes run independently but share a physical throughput of information as I/O data flows. The information interchange among the codes occurs during the run and is controlled by a "master" timing code.
The self-consistency of the field solution (electrostatic in the present applications) is assured by a technique which splits the simulation domain and provides to the field solver of each code the proper boundary conditions, maintaining the continuity of field and potential across the "merged" boundaries. This way each code can simulate a different plasma region with the most suitable space scale (e.g. a small grid size in the edge-plasma region to resolve the sheath length merged with a larger grid for the core plasma). The continuity of particle fluxes is retained as well.
The proposed approach is quite versatile: the information interchange is performed by diagnosed physical quantities (e.g density profiles, particle fluxes, electric field, velocity distributions) in a code-independent format, with no reference to the specific code representation (like computer particle properties or grid size).
The overall simulation is performed by a number of specialized modules (codes) properly connected each other. Each of these is provided with an interface which "translates" the physical information into the form which can be processed be the single code and viceversa.
Conceptually similar performances could be achieved by one "big" code that runs the different modules as "subroutines". However here the interconnection is done at the operating system level.
The present implementation with the UNIX InterProcess Communication Protocol (IPC) also allows the merging among codes running on different machines connected through the network.
Although this approach was conceived as mainly oriented to particle codes, the merging with other kinds of simulation codes, like the fluid ones, can be considered.
Reference running examples have been developed. As a first test for the basic features of the merging-code approach, like field solution self-consistency, particle fluxes continuity, code-independent diagnostics formats, as well as the software environment for providing the intercommunication features, a 1D-1D electrostatic merging was tried. Here one code simulates a tokamak-like plasma sheath region. A metal absorbing wall constitutes the left boundary while the right boundary is simply the "merging" "boundary" with the other plasma region (the core) where the second 1D code is referred to.
The 1D-1D merging provided an easy way for comparing the results with the same overall simulation performed with just one code on an extended domain.
A 1D-2D merging has been also considered. In this case the 1D run provides the (average) sheath electron density profiles to a 2D hybrid (particle-ion, Boltzmann fluid-electrons) code for ion sheath wave simulation, improving the previous model [2] where the same profile was approximated by an analytical expression.

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Far Field ICRF Sheath Formation on Walls and Limiters*

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The application of ICRF power has been established as an effective method of heating a tokamak plasma. Proper antenna phasing, alignment, and the use of low Z coatings have been successful in reducing the release of impurities from the antenna system to negligible levels. In large tokamaks operating in regimes of good single pass absorption, ICRF far-field-induced impurity release can also be made negligible. However, this best case scenario is difficult to achieve in small machines, or in regimes of moderate to poor single pass absorption, since significant rf wave energy exists near walls and limiters. In this case, rf sheath driven currents on walls and limiters are both expected and observed[1]. To assess this situation, a theory that unifies cold plasma wave propagation and rf sheaths is required. Model equations for this unified problem have been developed and solved by asymptotic matching techniques which enable rf sheath boundary conditions to be applied for a slow wave. The asymptotic procedure is made possible because of the disparity in scale lengths between the Debye length and the typical wavelengths of the cold fluid waves. The overall picture proposed is as follows: launched fast waves that are unabsorbed shine through the plasma to the far side of the tokamak where they are coupled to the slow waves by the boundary conditions imposed due to a "wall" or limiter. The slow waves then drive rf sheaths which are ultimately responsible for impurity production and convective perturbations of the edge plasma, in analogy to the impurity production[2] and convective cell[3] mechanisms in the near field, antenna driven case.

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MAGNETOFLUID DYNAMICS WITH ELECTRON PRESSURE AND INERTIA

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A reduced low frequency magnetofluid description is proposed that includes the effects of electron pressure and electron inertia as well as finite ion Larmor radius effects. The linear stability properties of the model are investigated analytically by means of an energy relation. For magnetically sheared equilibria it is found that an unstable interchange mode exists driven by a parallel current gradient and dependent upon electron temperature. A physical interpretation for the mode is given in terms of induced density fluctuations associated with magnetic perturbations due to the kinetic Alfven mode and the coupling of magnetic perturbations to the electron diamagnetic drift. In addition to the kinetic Alfven interchange mode, the model also describes a collisionless tearing instability due to electron inertia. Numerical computations of the full three-dimensional nonlinear model are presented and support the linear analytic results. Both the interchange and tearing instabilities are found to grow to significant amplitudes and ultimately result in the destruction of the magnetic flux surfaces and loss of density confinement. Possible implications of these results for Tokamak confinement are discussed.

Lower Hybrid Calculations for PBX-M†

by

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The PBX-M experiment with lower hybrid current drive plans to demonstrate deliberate modification of the current profile to improve plasma stability and beta. We have developed a calculation to support the experiment based on the Tokamak Simulation Code (TSC), and a package we call the Lower hybrid Simulation Code (LSC) which employs multiple ray tracing in general bean-shaped plasmas, and quasilinear damping of waves on electrons. We use electric-field-sensitive approximations to the current generated, as developed by Karney and Fisch.[1] The capability to model time-dependent current drive, including ramp-up and ramp-down, without actually solving the Fokker-Planck equation, has been applied to the parameters of PBX-M. We find typicallly two locations of damped power and induced current, these associated with the forward and back-ward going portions of the launched spectrum, and some difficulty damping the fastest waves launched by the coupler, which have $n_{||}$ in the neighborhood of 2.3. We estimate the effects of radial diffusion of fast electrons in the absorption process and and discuss an approach to including such effects in the calculation.

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TWO-DIMENSIONAL DETAILED MHD SIMULATION OF DEUTERIUM-FIBER-INITIATED Z-PINCHES

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Deuterium-fiber-initiated Z-pinch experiments have been simulated using a two-dimensional resistive magnetohydrodynamic model[1] which includes many important experimental details, such as "cold-start" initial conditions, thermal conduction, radiation, actual applied voltage vs. time, and grids of sufficient size and resolution to allow realistic development of the plasma. When the fiber becomes fully ionized (at a time depending on voltage ramp and fiber thickness), the simulations show rapidly developing m=0 instabilities drive intense non-uniform heating and rapid expansion of the plasma column. Diagnostics generated from the simulation results, such as shadowgrams and interferograms, are in good agreement with experiment[2]. Comparison of simulation-generated diagnostics with those from early experiments of this type suggests that visible light and shadowgram images of the plasma were misleading indicators of the stability and rate of expansion of the plasma column. Terms often dropped from the fluid model on the basis of small Larmor radius, such as the Hall term, may be significant in the Z-pinch[3,4]. Progress will be reported on the addition of such terms to the simulation.

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Tokamak Transport Based on the Thirteen Moments Model*

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Grad's thirteen moment approximation are used to study equilibrium and transport in a tokamak. In the 13 moments model the stress tensor and the heat flow are given by differential equations. A reduced set of equations is obtained by neglecting small terms. Small particle flows are included in the model. The effects of the stresses and of the heat flows are included consistently. An expansion in a small parameter is used to determine the equilibrium and obtain the evolution of the equilibrium on the transport time scale.

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Stationary 3D Vlasov Plasma Equilibria with FLR Effects.*

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Previous models of Tokamak equilibrium with mass flow have been limited to an axisymmetric MHD description. For example, see Cooper and Hirshman[1]. We find a 3D Vlasov description of the static electric and magnetic fields in a Tokamak plasma with steady shear flow. The plasma current is given by the sum of the currents due to the guiding-center drift velocities of the ions and electrons and the diamagnetic current. The first contribution is calculated by multiplying Littlejohn's equations[2] for the guiding-center drift velocities of the ions and electrons to second order in m/e by an appropriate distribution function and integrating over velocity space, and the diamagnetic current is then added to give the total. Moments of the distribution function which appear in these equations are evaluated to appropriate order using a Vlasov distribution function which is a function of the approximate constants of the motion. The magnetic field is calculated from the currents by Ampere's Law using a collocation method similar to that used by Anderson[3] except that the basis functions for the vector potential have continuous third derivatives, as is required to calculate the second order terms in the expression for the current. Magnetic islands and shear flows arise naturally in this formulation.

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** Work performed toward Ph.D. at UC-Davis.

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Operational Scenarios for a Steady-State Advanced Tokamak (SSAT)

W.M. Nevins and the TPX Team

A steady-state advanced tokamak has been proposed to develop the database needed to design an attractive fusion demonstration reactor. The SSAT must have a support many operational regimes to provide the necessary data. Four categories of operating scenarios for the SSAT are:

1. **High-beta, Standard Tokamak Operation.** Full-current steady-state operation at operational limits in β ($\approx 3.5\ I_p/aB_0$) and q_ψ (3.0) similar to those used in machine designs based on the present tokamak data base (e.g., ITER or BPX).

2. **High Bootstrap Current Fraction, 1^{st} Stability Operation** with bootstrap current fractions exceeding 66%.

3. **Second Stable Operation** in which the β-limit is extended, consistent with our best theoretical understanding of MHD stability limits with current profile control.

4. **Advanced Confinement Operation**, in which control over the current, density, and pressure profiles, together with control of plasma/surface interactions is used to access, in steady-state, advanced confinement modes that are seen transiently in present tokamak experiments.

These operating modes will be described in detail, and the ability of other tokamaks in the world program to address the SSAT mission will be discussed.

Review Lecture, 1992 Sherwood Fusion Theory Conference

New Mathematical Methods for Linear Plasma Problems*

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Within the last few years, a number of powerful new mathematical tools have become available for the solution of linear plasma problems (and eventually for nonlinear problems). This review will be devoted to two areas: (I) the linearized Vlasov equation, and (II) multi-component wave fields in multi-dimensional phase space.

In (I), we discuss *(a)* the use of a pseudo-Hilbert space [1] (with indefinite metric) for the set of Lie generating functions [2], to make the linearized Vlasov-Maxwell system Hermitian, a desirable property; and *(b)* the deformation of the linearized Vlasov operator into complex phase space [3], so that the complete set of deformed Case-van Kampen modes includes resonantly damped collective modes.

In (II), we discuss revised eikonal theory, allowing arbitrarily large spatial gradients; generalized Fourier transforms, intermediate between **x**- and **k**-representations [4]; natural coordinates and normal forms for mode conversion [5,6]; Hermiticity-preserving reductions of multi-component wave equations [7]; and geometric phases in mode quantization [8].

If time permits, some applications of these methods will be discussed.

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The Interaction of Energetic Alpha-Particles with Intense Lower Hybrid Waves†

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Lower hybrid waves are a demonstrated, continuous means of driving toroidal current in a tokamak. When these waves propagate in a tokamak fusion reactor, in which there are energetic α-particles, there is a concern that these waves may be absorbed by the α-particles, and not by the electrons. In fact, for heating by very intense waves, the α-particles tend to absorb more wave power than do the electrons, because the electron interaction exhibits quasilinear saturation, *i.e.*, the electron velocity distribution flattens in the region where the wave phase velocities are finite. The α-particle interaction exhibits no saturation, because once in resonance, the α-particle remains in resonance even as it gains energy. In such a case the current-drive efficiency would diminish greatly.

What we show, however, is that there are conditions under which the α-particles do not appreciably damp, and may even amplify, the wave, thereby enhancing the current-drive effect when the power is eventually absorbed by electrons. Waves traveling in one poloidal direction, in addition to being directed in one toroidal direction, are shown to be the most efficient drivers of current in the presence of the energetic α-particles.

The waves are to be absorbed in the region of the largest density gradient to the energetic α-particles, as the lower-hybrid rays circle the magnetic axis. The amplification occurs at the expense of the free expansion energy of the α-particles, and if this happens, there would be favorable side effects, in that less of the α-particle energy would then be available to fuel unwanted instabilities, and some helium ash would be transported to the tokamak periphery. Any α-particle power channeled into the current drive is very valuable, because there it is not first converted to heat, then to electricity, then to lower hybrid power, and only then to power the current drive. Of sufficient interest, however, is merely to avoid the α-particle damping and to choose the favorable poloidal direction.

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Energetic Alpha Particle Induced Bootstrap Current

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The neoclassical bootstrap current is of great importance in modern and future day fusion devices because it can contribute a substantial fraction of total plasma current provided there exists a sufficient poloidal beta gradient. Typically, the fusion produced fast particles may have their beta gradient comparable with background gradient (e.g. at $T_i = 20$ keV, $\frac{\frac{\partial}{\partial r}\beta_\alpha}{\frac{\partial}{\partial r}(\beta_e+\beta_i)} \simeq 0.5$). One thus expects that these fast particles can significantly modify the bootstrap current. Previously, the α particle induced bootstrap current has been calculated by keeping only the slowing down drag in the alpha collision operator.[1,2] However, in a recent paper[3] it has been shown that pitch angle scattering does play a role in the neoclassical transport process of fast α particles. For the bootstrap current pitch angle scattering is essential. In the present work the α induced bootstrap current is calculated by including effects of finite aspect ratio, slowing down drag, and pitch angle scattering, further extending the work of Ref. [3]. As an application, the bootstrap current, including conventional and α induced contributions, will be evaluated based on ITER parameters.

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ON THE POSSIBILITY OF A STEADY STATE TOKAMAK MAINTAINED BY BOOTSTRAP CURRENT DRIVE ALONE

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Some experiments at UCLA by Robert Taylor indicated the possibility of steady state current drive in a Tokamak, driven by plasma flows alone. Recently, 2-1/2 D particle simulations by William Numan at UCLA using a quasi-torodial geometry, with loss of plasma at a circular limiter and refueling at the center show that the flow not only maintains the current but can actually cause it to increase. Increases in the total current of 20% have been observed with no indication of saturation. In these simulations the loss appears to be driven by convective cell diffusion. While what is going on is undoubtedly different from what occurs in real Tokamaks, we believe that there are many similarities in that convective losses probably play an important roll there. We believe that there is excess current being generated in the outer regions of the plasma by the Bootstrap effect and some of this current is transported to the center to provide the seed current needed by the conventional theory. We have constructed an analytic model based on modifying Ohm's Law by including a current diffusion term. The theory shows that for sufficiently rapid particle loss the current is totally sustained, and if the loss rate is larger the system can even act as a generator (power can be extracted from the transformer). Whether or not this is possible in a real Tokamak depends on the ratio of current diffusion (which is not known very well) to plasma diffusion. Results will be presented from the simulation and the analytic theory and some discussion of a number of mechanisms that contribute to current diffusion will be given.

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Electron-Temperature-Gradient Turbulence in Tokamak Scrape-Off Layers*

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A vociferous instability driven by electron temperature gradients in the presence of end loss and ion polarization drift[1] is a promising candidate to account for cross-field transport in tokamak scrape-off layers.[2] Understanding the physics of the cross-field transport is important as it determines the thickness of the scrape-off layer (SOL) and therefore the heat flux on the divertors or limiters, and it may also be relevant to the H-mode transition. We review the theory outlined in Refs. 1 and 2, and discuss several extensions. These include a derivation of the mode equation which includes the transition between electrostatic and low-β electromagnetic regimes, a comparative evaluation of various nonlinear terms, a discussion of damping mechanisms, an improved evaluation of finite $k_{\parallel}$ effects, and some rudimentary nonlinear theory. The nonlinear treatment includes mixing-length estimates, a simplified one-point renormalization calculation, and a scaling analysis, all of which are mutually consistent. We qualitatively discuss implications for the wave spectrum. We also show the results of numerical calculations of self-consistent one-dimensional (radial) modelling of a limited plasma scrape-off layer, using the theoretically obtained transport coefficients. Finally, we discuss the (reasonable) consistency of the theory with experimental observations in terms of both fluctuation characteristics and equilibrium parameter variations. Related particle simulations[3], as well as calculations of coupling with the core plasma [4] and more detailed nonlinear work[4,5] are presented elsewhere at this meeting.

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PHYSICS PRINCIPLES OF IGNITION EXPERIMENTS[1]

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The rise of the plasma current in magnetically confined, toroidal experiments designed to reach fusion ignition conditions can be tailored [1,2] to maintain a strongly inhomogeneous longitudinal electric field, with a minimum at the center of the plasma column, up to temperatures where the heating due to D-T fusion reaction products is significant. Thus a substantial contribution from the ohmic heating can be maintained up to these regimes and ignition achieved without reaching the conditions where a substantial degradation of the energy confinement time may be expected, on the basis of experiments where the ohmic heating power P_Ω is negligible relative to that (P_{INJ}) of the externally injected heating. A free boundary transport code has been used to demonstrate this for the case of tight aspect ratio plasmas ($R_o/a \simeq 2.7$) with elongated cross sections ($B/a \simeq 1.85$) characterized by high toroidal currents (e.g., $I_p \lesssim 12MA$ for $B_T \simeq 13T$ and $R_o \simeq 1.3m$), high current densities ($< J > \lesssim 0.9kA/cm^2$) and considerable paramagnetic currents ($I_\theta \lesssim (3/4)I_p$). The transport model that we have adopted has two components. One, that has been well tested for experiments where ohmic heating is dominant, produces well behaved "canonical" temperature profiles and gives the nearly invariant value of the loop voltage ($V_{\|} \simeq 1-2$ Volt) that is characteristic of these experiments. The other component prevails when ohmic heating ceases to be dominant. It also produces realistic profiles, leads to a scaling of the energy confinement time that is consistent with those existing experiments where injected heating is prevalent, and is derived from the combined theory of the (ubiquitous) trapped electron mode and of edge modes driven for instance by the impurity density gradient. Under these conditions, ignition can be reached with peak plasma densities $n_o \simeq 10^{15} cm^{-3}$, peak temperatures $11 \lesssim T_o \lesssim 15keV$, relatively low values of the α-particle power $P_\alpha \lesssim 20MW$, and ratios $P_\alpha/P_\Omega \lesssim 2$. The plasma density profile is assumed to be prevented from being flat by pellet injection techniques. The high particle densities, the high magnetic fields, and the relatively low values of the thermal loading on the first wall favor a good degree of plasma purity ($Z_{eff} \lesssim 1.6$). The volume where the magnetic parameter $q \leq 1$ and macroscopic $m^o = 1$ plasma modes may be excited, can be shown[1,2] to remain small until ignition is attained. The stability margin against these modes is made uniquely favorable by the low values of $\beta-$ poloidal that characterize low temperature ignition. An injected heating source (e.g., ICRF) is used to broaden the scenerios under which ignition is achieved. The benefit of enhanced confinement regimes, such as the so-called "ohmic H-mode" recently investigated by an extensive series of experiments by the Tuman machine, and of the so-called "p-mode" obtained by combining the injection of pallets with strong injected heating at the center of the plasma column is considered as a further margin to achieve the desired conditions. The conclusions reached for the current rise process, the transport models to be adopted, and the relevance of ohmic heating are applicable to all advanced ignition experiments.

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Application of Plasma Theory Techniques to Fusion Engineering Problems: A Fast Solver for the Time Evolution of the PF Currents

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An important problem in the design of tokamak experiments is the determination of the time dependent PF currents required to produce a given desired plasma evolution. For a realistic evaluation, one must also include the induced eddy currents in the vacuum chamber. This last requirement significantly increases the difficulty of the PF calculation for two reasons. First, without the vacuum chamber, there are typically less than 10 independent PF currents to determine, usually by means of a regularized optimization procedure. The vacuum chamber is typically modelled by approximately 100 passive filaments thereby increasing the complexity of the problem to that of a regularized optimization of 110 filaments subject to 100 constraints. The second problem involves time scales. In most cases of interest the plasma current evolves on a plasma resistive diffusion time scale. However, since the vacuum chamber is usually constructed of stainless steel, its L/R time is much shorter, by more than an order of magnitude. To accurately evolve these currents one needs to either take a large number of time steps or use more sophisticated implicit time advance algorithms. We have developed a fast and robust technique for resolving these difficulties. Our procedure makes extensive use of the multiple time scale procedure. For $t > t_{vac}$, the vacuum chamber currents are accurately given by their adiabatic solutions which reduces the optimization problem from one involving 110 currents to one involving 10 currents. For $t < t_{vac}$, the first order correction to the adiabatic solution is found by the multiple time scale expansion, thereby leading to quasi-analytic solution. Since the fast evolution is known analytically, the numerical system evolves on the slow time scale, and straightforward time advance algorithms with large time steps can be used. Results will be presented at the meeting.

Net Transport Across Fluctuating Flux Surfaces*

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We investigate particle and convective energy transport in a fluid moment description of a plasma that allows for kinetically and nonlinearly determined stress tensor closure relations.[1,2] We assume the existence of closed, nested canonical magnetic flux surfaces for each fluid species and use an expression for the surface motion from the flux invariant[3] generalized to the canonical magnetic field $\mathbf{B}_\# = \mathbf{B} + (m/q)\nabla \times \mathbf{V}$. For the electrons, this field and the magnetic field are essentially equivalent due to the small electron mass, but for the ions the vorticity term yields slightly different flux surfaces. The relationship between the motions of the fluids and the surfaces is explored. Using an ideal, isentropic lowest order representation for each fluid yields no lowest order fluid flow across the surfaces. The lowest order fluctuations therefore produce no radial particle or convective energy transport. Including the entropy producing effects yields cross surface transport directly from the viscous stress and friction force and indirectly from these dissipative effects through the loop voltage and a species dependent scalar potential gradient. Because the particle transport from the scalar potential gradient fluctuations is limited by parallel momentum dissipation, we find that for typical tokamak parameters the electron scalar potential fluctuations may be large enough to account for the edge electron particle transport but are apparently too small to contribute substantially in the core. In this model, with closed surface topology, anomalous cross surface electron particle and convective energy transport in the core may evidently only result from the electron toroidal viscous stress. For the ions, much larger core ion particle transport may result from the different ion scalar potential term. In the absence of an anomalous electron toroidal viscous stress, however, at least the electron transport would have to result from destruction of the closed surface topology.

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Application of Plasma Theory Techniques to Fusion Engineering Problems: Quench Protection in Superconductors

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Some of the mathematical techniques often utilized in plasma theory are used to analyze the quench process in a superconducting magnet. The system under consideration consists of superconducting wires, and supercritical helium which is used for the cooling of the magnet. In the event of a localized phase transition of the superconductor into its normal state, for instance due to a local temperature perturbation, joule heating is initiated and the normal zone propagates along the conductor (i.e. the magnet quenches). This quench process poses an essential safety criterion for the magnet. The governing one dimensional mass, momentum and energy equations are derived using the multiple time scale expansions (analogous to deriving 1-D transport equations in a tokamak as a result of rapid cross field equilibration). High rate of heat transfer between the wires and the helium allows the reduction of the number of unknown variables in the system (analogous to electron-ion equilibration). The helium mach number is small in many quench events and the inertia terms in the momentum equation can be neglected, greatly simplifying the system (analogous to quasi-state evolution of the Grad-Shafranov equation).

Low β Ideal MHD Stability of DIII–D Revisited: Wall Stabilization

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The effect of wall stabilization from the vacuum vessel on low β current-driven modes in DIII–D is considered. The stability of DIII–D to current-driven modes, with no wall stabilization, has been reported at earlier conferences [1,2]. There, the stability boundaries were determined for a reference $\kappa = 1.8$ limiter configuration in the (q_0, q_s) parameter space, where q_0 is the safety factor q on axis and q_s is the value of q at the limiter. In this parameter space, the stable regime is limited at high q_0 by a staircase boundary of alternating constant q_0 and constant q_s steps. The low q_0 limit is $q_0 = 0.8$. At a given q_s, wall stabilization from the DIII–D vessel is found to have a strong effect on both the upper and lower q_0 stability limits by widening the stable range of operation. On the other hand, the constant q_s limits are unaffected. Of particular importance is the fact that the low β current limit of $q_s = 2$ is not changed by the presence of the DIII–D wall. The underlying reason for this is rather subtle, however. With a wall at infinity, there are actually two unstable modes. The mode with the higher growth rate — the predominantly $m = 2$ external kink — is stabilized by the DIII–D wall, but the second mode is not. In some cases, this second mode is of the quasi-interchange type but, in others, it is predominantly an $m = 3$ external kink. A similar result seems to hold whenever there is no rational surface in the plasma. This result and the influence of the wall on the other stability boundaries will be discussed in detail. The results are also shown to be quantitatively consistent with the available DIII–D data appropriate to this reference configuration. The results may also help to explain the role of the stabilizing plates in PBX–M. However, it is not possible from this analysis to definitively determine whether wall stabilization really does play a role experimentally in DIII–D. Possible experiments in DIII–D to resolve this uncertainty will be discussed.

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Kinetic Description of Toroidal Alfvén Eigenmodes*

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Heating of tokamak plasmas by toroidal Alfvén eigenmodes[1,2] and toroidicity-modified global Alfvén eigenmodes is investigated. These modes may be viewed as resulting from the coupling of cylindrical poloidal harmonics. A previously constructed antenna-driven cylindrical code,[3] which takes into account electron inertia and Landau damping, finite Larmor radius, the equilibrium current, and magnetic shear, is used to study this numerically. We compute the wave electric field, energy deposition, energy flow as functions of minor radius. The eigenmodes are identified as resonances in the impedance Z(ω) (total energy deposition as a function of the transmitted frequency).

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Effects of Sheared Toroidal Rotation on Single Particle Dynamics, Nonlinear Gyrokinetics, and Wave-Particle Interaction*

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Ion orbit in a toroidally rotating plasma is analyzed using the action-variational method in the extended phase space. Sheared flow induces ellipicity of Larmor orbit, modification of the first adiabatic invariant μ. Consequently, the nonlinear gyrokinetic equation is modified, and can be expressed in terms of the effective potentials,[1] $\mathbf{A}^* = \mathbf{A} + \mathbf{V}_0 + c_{\|}\,\mathbf{b}$, and $\Phi^* = \Phi + v_E^2/2$. The first order corrections (in ρ_{pi}/L_v) to the second adiabatic invariant J, the bounce frequency ω_b, the precession frequency ω_d, the banana width, the transit frequency ω_t, and the fraction of trapped ions, are obtained for $V_{0\varphi}$ on the order of V_{Ti}. This orbit modification effects on the strength of various kinetic instabilities driven by wave-particle interactions are also investigated.

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Transport in a Stochastic Magnetic Field

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Abstract
Heat transport in a stochastic magnetic field configuration is investigated analytically and numerically with two complementary models: A Chirikov-Taylor map model and a Gaussian random field model. Numerical solution of the Chirikov-Taylor model shows a short-time nonlocal regime, but at large time the Rechester-Rosenbluth effective diffusion regime is confirmed numerically. The Gaussian model, for which the associated nonlocal propagator is calculated, describes this short-time behavior. Subdiffusive behavior is observed for short mean free paths near stochastic threshold.

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MHD Tilt Stability of Non-Stationary Spheromaks

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Abstract. A spectral, 3-D, time-dependent MHD code is developed for the purpose of studying the tilt instability in realistic, dynamic spheromaks. This code is first tested against previously published results, and yields excellent agreement. Using this code, a preliminary study of a rotating spheromak is performed to find that a spheromak that is initially stable against tilting can be driven unstable by increasing its rotation beyond a threshold. This preliminary study is then improved by attaching this stability code to a sophisticated 2-D, time-dependent code, HAM. With the aid of the HAM code, the 3-D code will simultaneously determine the stability against tilting of rotating (or accelerating) spheromaks as they vary in time.

Specific Transport Process under ECRH in Tokamaks*

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A new transport mechanism is suggested appearing specifically under cyclotron wave heating of plasma in toroidal devises. This mechanism can explain the deterioration of particle confinement in the resonant zone and other experimentally observed phenomena accompany electron cyclotron heating.

The driving force for the new transport process is the poloidally asymmetric electrostatic potential. This potential arises due to the enrichment of the population of suprathermal banana electrons bouncing at the resonance position. Such the accumulation of high energy particles during cyclotron heating is a well known phenomenon and have been studied both theoretically and experimentally in mirror machines.

The poloidally asymmetric electrostatic potential strongly influences on the particle's trajectories. The most pronounced effect is the formation of the group of thermal particles trapped into the poloidal inhomogeneity of the electric field. This group of particles can drift in vertical direction causing an enhanced transport at cyclotron resonance position.

Along with the appearance of the electrostatic potential well at resonance position there is a possibility of the formation of the similar electric field asymmetry at the inner circumference of the torus due to accumulation of high energy passing electrons. Such the potential well leads to the enrichment of impurity population at this location and can be a trigger for the MARFE phenomena if the cyclotron heating zone is sufficiently close the periphery.

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Transport Simulation of Oscillating Gas-Puff on TEXT using Theoretical Models*

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We extend our previous studies[1] of the oscillating gas puff on the TEXT tokamak, using the transport code CHAPO with a variety of theoretical models. By comparing with the amplitudes and phases of the experimental perturbed fluxes, densities, temperatures, and fluctuation levels,[2] we attempt to quantify the need for inward pinch terms in the models.[2,3]

A perturbation analysis has been developed which closely couples measurements of oscillating density, temperature, and fluctuation levels with a theoretical model in order to calculate perturbed particle fluxes.[2] Perturbation data on TEXT yielded a flux, calculated using a simplified dissipative-trapped-electron (*dte*) model, which did not agree with the directly measured flux. The lack of inward steady-state flux terms in the model may contribute substantially to this disagreement. In a complementary exercise, we carried out simulations with anomalous transport models that retained the *dte* scaling but allowed for *ad hoc* off-diagonal elements, *i.e.*, including various pinch terms.[1] The results were ambiguous, however, owing to the uncertainty in the particle source in the plasma core at the low plasma densities considered. Here, we extend the simulation studies, reexamining the source question, considering additional models, and extending the analysis to higher density cases where the effect of the source is reduced.

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MAGNETIC RECONNECTION IN ELECTRON-MAGNETOHYDRODYNAMICS

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The magnetic field dynamics and reconnection processes in a highly conducting plasma are investigated in the regimes where Ohm's law is dominated by the Hall term, using a single (electron) fluid description (Electron-magnetohydrodynamics). In these regimes, which correspond to the frequency range of the so called whistler (helicon) mode, the electromagnetic field is nearly force-free: $(\mathbf{j} \times \mathbf{B})/c + en_e \mathbf{E} = 0$.

The evolution of the magnetic field in the vicinity of an X-line is discussed in the linear and in the non-linear regimes. The propagation of whistler waves results in the steepening of their wave front and in the increase of the electric current density in the neighbourhood of the magnetic separatrix surfaces.

Small scale magnetic reconnection occurs near surfaces where $\mathbf{k}\cdot\mathbf{B} = 0$, with $\mathbf{k}$ the mode wave-number, and tearing-type modes can be unstable due to the effect of electron inertia.

A class of exact self-similar solutions is obtained. These describe, within the scope of a local approximation, the non linear time development (magnetic collapse) of the singularities that occur in three-dimensional magnetic configurations. Flat electric current sheets are formed during this collapse.

PERPENDICULAR ION ACCELERATION AT FREQUENCIES LARGER THAN THE ION-CYCLOTRON FREQUENCY*

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This study is motivated by the ubiquitous[1,2] observation of perpendicular fast ion generation under conditions that do not correspond to conventional cyclotron-resonance heating. The essence of the problem is that ions circulate relatively slowly through RF fields that have a sharp spatial gradient across their Larmor radius. This interaction is relevant to several topics, including: ICRF antenna performance, LH and fast wave current drive, alpha particle relaxation, and dissipation of Alfven-wave filaments. A 2-1/2 D, magnetized, particle simulation code is used to explore this process. It is found that at the plasma edge fast ion "jets" are formed in synchronism with the RF cycles, while in the interior perpendicular-Landau damping by large orbits ions occurs. Analytic models of the key physical features are considered.

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ELMS as a Kelvin-Helmholtz Instability*

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ELMs may be a Kelvin-Helmholtz instability caused by the sheared rotation of H mode plasmas. The Kelvin-Helmholtz instability is stabilized by coupling to Alfven waves. There is a critical velocity gradient, of order of the Alfven velocity divided by the magnetic shear length. This is verified in a numerical simulation. The critical velocity shear is consistent with experiment. A nonlinear simulation shows how the Kelvin-Helmholtz mode can cause periodic nonlinear sawtooth-like oscillations of the velocity profile.

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The Performance of a Fluid Code on Massively Parallel Machines*

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The performance of the KITE code on the Oak Ridge Intel hypercube, the JPL Intel hypercube and Delta machine, and the TMC Connection Machine at Los Alamos will be compared with the performance and cost of other machines. With the collaboration of the JPL group, it has been possible to complete the code optimization studies on the hypercube, that is, to find the optimal number of processors for a problem of a given size. From these results, we will present the main characteristics of the next-generation hypercubes needed for plasma turbulence calculations. Timings of convolution routines optimized for the Connection machine will also be presented.

The KITE code is an initial value, three-dimensional, nonlinear, seven-field code used for plasma turbulence studies. The main components of the code are convolutions of Fourier harmonics and block tridiagonal matrix solves. Direct allocation of all arrays in the KITE code to the nodes of the Intel hypercube has allowed full use of the 128 nodes on the ORNL Intel iPSC/860 hypercube. Using this configuration and recent improvements in the compiler, we have a factor of 5 speedup over a single-processor Cray-II. The JPL Intel hypercube (64 processors, 16 Mbytes per processor) complements results of the ORNL hypercube (128 processors, 8 Mbytes per processor) by having more memory per processor.The output for the restarts and analysis of this code has been changed to a machine independent XDR binary format so we do not loose precision on the restarts and we can analyze this data on workstations from an optical disk.

Also with JPL collaboration, the first runs of this code on the Touchstone Delta machine have been made. A 25% speedup has been found for the same number of processors (128) as the ORNL hypercube. This is because of the faster communication processes in the Delta machine. A run has been made on all 512 nodes of the Delta. The speedup was a factor of 16 over a single-processor Cray-II. This run had only 2 grid points per node and 1 Fourier harmonic per node, so we are planning other runs that will be of more optimal size for 512 processors.

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Gyrokinetic Particle Simulation of Impurity Transport*

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Gyrokinetic particle simulations of ion temperature gradient driven (η_i) instabilities have been carried out in three-dimensional slab and toroidal geometries[1]. The purpose of the study is to understand the physics of the inward pinch of impurity ions due to microturbulence. We have examined the conditions necessary for such a pinch to exist, and how the average pinch velocity is influenced by such factors as impurity mass, charge, and temperature. The simulation results indicate that an inward pinch does indeed exist. In particular, we have found that the average inward pinch velocity scales as Z/m for cold impurities, while the pinch is reduced for higher temperature impurity ions depending on their thermal velocities ($v_t = \sqrt{\frac{T}{m}}$). In the case of impurity ions with temperatures comparable to the background temperature, the largest pinch is associated with the impurities of largest mass and charge; e.g. warm Fe^{24+} exhibits a larger pinch than warm He^{2+}.

The basic driving mechanism for the inward pinch is the acceleration of the impurity ions along the magnetic field lines by $E_{||}$. By treating the impurity particles both self-consistently and as test particles we have gained a better understanding of the mechanism responsible for the pinch. The results indicate that the average inward pinch velocity is reduced (although the total inward impurity flux increases) as the impurity ion concentration is increased. A theoretical understanding of this phenomena will be presented.

The nonlinear stage of the simulation has also been investigated. After saturation, the magnitude of the average inward pinch velocity is reduced while the saturation amplitude of the background modes remains the same indicating that the pinch velocity is not simply proportional to $\sum |\phi_k|^2$ but rather it may be related to the phase differences between n_k and ϕ_k of the various modes in the system. Comparisons will be made between the flux level predicted by the particle code and quasilinear theory as well as other non-linear theories.

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[1]Codes developed in conjunction with J.V.W. Reynders and S.E. Parker

RECONNECTION DRIVEN BY ELECTRON PRESSURE AND THE FAST SAWTOOTH CRASH

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Experimental measurements of the sawtooth crash time τ_c in the TFTR and JET tokamaks range from 20 to 2000 μsec. The crash time, based on a Sweet-Parker model of resistive reconnection by the $m = 1$ tearing mode is of the order of 2000 μsec, which is short enough to explain the slow crashes, but not the fast crashes.

In a previous paper[1] we showed that the electric field E induced during magnetic reconnection during the sawtooth crash greatly exceeds the Dreicer field E_D, and, therefore, classical resistivity cannot play a role in this process. Including electron inertia in Ohm's law, we found that during collisionless reconnection the current layer collapses to a thickness which is much smaller than the ion gyroradius ρ_s.

Here, we show that the extreme narrowness of this current layer alters the parallel force acting on the electrons. The polarization drift of the ions across this very narrow current layer formed during reconnection causes a perturbation in the ion density. The electrons move rapidly along the magnetic field lines to charge neutralize this ion density perturbation, leading to a large parallel gradient in the electron pressure. We examine the effect of this parallel pressure force on the reconnection process. We present numerical simulations of magnetic field line reconnection using an Ohm's law which includes the effect of the parallel electron pressure gradient. When the width of the resonant current layer is less than ρ_s, we find that the parallel pressure force induces a further contraction in the width of the current layer. Furthermore, not only does the current layer contract in the direction of the plasma inflow to the X-point, but the current layer also shrinks in the direction of the outflowing plasma. At the same time, the plasma flow in the dissipation region detaches from the current layer, the width of the outflowing plasma layer increasing to ρ_s. As a consequence, the rate of reconnection of magnetic field lines increases leading to a fast sawtooth crash.

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Monte-Carlo Simulation of Kinetic Transport Near the Tokamak Edge*

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Particle and momentum transport of ions near the loss boundary in an axisymmetric tokamak is being studied by a Monte-Carlo method that simulates the pitch angle scattering[1] along with the ion guiding-center orbit integration. Emphasis is laid on the comparison between the ion transport with and without electric field, because the ion orbit response to the electric field could be much more complicated than an analysis[2] involving the electric field turning points. The results of the simulation and comparison with the theories[3] will be presented.

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1992 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

Stochastic Broadening in a Single-null Divertor Tokamak

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ABSTRACT

Magnetic perturbations cause the region around a separatrix to become stochastic. The plasma particles following the field lines are led into the stochastic region by diffusion, where they strike the divertor plate. The foot-print on the divertor plate may consist of a single or more curves [1]. We have used the discrete map $X_{n+1}=X_n-k(Y_n-Y_n^2)$, $Y_{n+1}=Y_n+kX_{n+1}$ and its continuous analog to model the magnetic topology of a single-null divertor tokamak [2]. We find that the foot-print undergoes a bifurcation from a continuum to multiple strips at a critical value of the diffusion coefficient D as it become small. For the continuum case, the average width of the foot-print varies as the fourth root of D. For the trajectories emanating in the stochastic layer at X=0 in the principal plane inside the separatrix with D=0, the dwelling time for the particles striking the plate has a fractal structure. Also, for these trajectories, the reverse map emanating from the foot-print on the divertor plate always circle the magnetic axis before striking the other side of the divertor plate. The reverse trajectories emanating from the blank regions do not circle the magnetic axis. At present, we are investigating whether the dark and blank regions on the plate have self-similar structure. Future plans are to study the map for double-null divertor with effects of velocity-space scattering and diffuser coils. This work is supported by US DoE DE-FG05-ER53265 and DE-FG05-90ER54106.

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Abstract for 1992 Sherwood Theory Meeting

NON-STANDARD HIGH ENERGY ION ORBITS: SLOWING DOWN AND MHD STABILISATION

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During intense ICRF-heating in JET, the resonating minority ions are often accelerated up to energies in the MeV range. For such ions, the standard "banana" orbits are distorted near the magnetic axis into "potato-shaped" orbits with a characteristic width $\delta_p=(2q_o v_\perp/\Omega R)^{2/3}R$. For a 1MeV hydrogen ion in a JET-like environment, $\delta_p \sim 30$cm. Since, in JET, the width, r_*, of the RF absorption region is typically of the order of or less than 30cm, most minority ions acquire non-standard potato orbits during on-axis high power ICRF-heating.

We present an analytic solution of the Fokker-Planck equation, which takes into account the actual orbit characteristics. In particular, we have considered the outward radial movement of the tip of the potato orbit as the particle slows down in energy. The resulting fast ion pressure profile is found to have a width of the order of the typical orbit width, δ_p. Furthermore, a non-standard fast ion current is found, which can be of the order of a few hundred kA in a JET-like plasma.

The stabilising influence of fast ions with large orbit widths on internal kink modes has also been investigated. The maximum stabilising effect can be obtained by focussing the RF field as much as possible on the magnetic axis. Neglecting the orbit widths ($\delta_p \to 0$) grossly overestimates this focussing effect by predicting $\delta W_{hot} \propto r_*^{-1}$, while we find that δW_{hot} becomes practically insensitive to r_* for $r_* < \delta_p$ (here, δW_{hot} is the fast ion perturbed energy integral). Stabilisation is hindered when the average potato width becomes comparable with the q=1 radius, r_s. Typically, on JET, $r_* < \delta_p < r_s$, and δW_{hot} is reduced by 20-40% compared with the value of δW_{hot} obtained by neglecting the finite orbit widths.

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Bootstrap Current Driven by Energetic Ion Species in Tokamaks*

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In a tokamak with fusion reacting plasma or with heavy neutral beam injections, energetic ions can possess a significant fraction of the total plasma energy and can exhibit a quite steep pressure gradient in the burning core region. As a result, the bootstrap current driven by energetic ions can be an important factor in determining the toroidal electrical current profile. Previous neoclassical theories considered electron slowing-down collisions only to calculate the hot ion bootstrap current. However, it is known that the ion pitch-angle scattering plays an important role in the transport mechanism of energetic ions [1]. A variational theory is developed to calculate the hot ion bootstrap current in a general geometry with both slowing-down and pitch-angle scattering effects included, and a bootstrap current level significantly enhanced from previous results is found. It is found the magnitude of hot-ion-driven bootstrap current is of order 20-30 percent of the total background bootstrap current in a typical ITER-like operation regime. Modification to total current profile is more significant than the magnitude itself due to higher concentration of the hot-ion bootstrap current in the burning core region.

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ICRF Fast Wave Current Drive and MHD Equilibrium Model*

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Recently a toroidal full-wave ICRF code (FISIC)[1] was modified to include the combined effects of electron Landau damping (ELD) and transit time magnetic pumping (TTMP)[2]. This code has now been combined with a parameterization (G_p) of the current drive efficiency[3] obtained from an adjoint solution of the Fokker Planck equation. The rf current density profile is then obtained by taking $J_{rf}(\rho) = G_p S_{rf}(\rho)$, where $S_{rf}(\rho)$ is given by the full-wave ICRF code and $G_p = G_p(Z_{eff},\ \epsilon,\ \theta,\ v_{\parallel}/v_{te})$ includes the effect of particle trapping. At present this fast wave current drive model is being incorporated into a combined equilibrium and current drive calculation (ACCOME)[4,5]. The ACCOME model incorporates a free boundary solution of the Grad Shafranov equation with the calculation of driven currents due to neutral beams, lower hybrid waves, an ohmic electric field, and bootstrap effects. The current drive and equilibrium packages iterate between each other to obtain an MHD equilibrium which is consistent with the profiles of plasma current density. Model results will be presented for the proposed TPX and ITER devices.

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Profiles Marginally Accessible to the Second Region of Stability *

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The determination of the equilibrium profiles for accessing the second region of stability against ballooning modes in tokamak plasmas is a major problem in MHD stability studies, especially more so at present, since many devices have the capability to at least get partially into the second region. There are, at present, considerable variation and qualitativeness in the theoretically predicted profiles. This is largely due to the fact that there are few constraints on the current or pressure profiles necessary to reduce the space of the parameter search. One way to obviate this is to constrain these profiles such that they are *marginally stable at the accessible point for most every flux surface* (the surfaces near the origin are usually infinitely stable or unstable so there can be some arbitrariness there). This point can be chosen to be at the minimun of the stability boundary curve in the $s - \alpha$ plane. This procedure gives unique prescriptions for $p'(\psi)$ and $q'(\psi)$, and since we can require $p(0) = 0$, then $p(\psi)$ can also be unique, but $q(\psi)$ will be determined only to within, say, $q(0)$. Thus these profiles will depend only on *aspect ratio, cross-section shape and* $q(0)$. At the very least, these profiles can be a starting point for searching for 'experimentally reasonable' ones since the current profiles derived from this technique cannot be specified arbirtrarily.

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FURTHER STUDIES OF FLOW EFFECTS ON LONG WAVELENGTH DRIFT WAVE TURBULENCE

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Recently, wide attention has been drawn to the idea of suppression of turbulence by the flow generated from turbulence and its relation to the L-H transition in tokamak edge plasma. In a previous study by Carreras *et al*‡ the sheared $\mathbf{E} \times \mathbf{B}$ flow (V_0') effects on the long wavelength drift wave turbulence were discussed. In that work, qualitative difference in the predictions between linear and nonlinear theories were shown, and it suggested that the turbulence is spiky, radially-intermittent near a low q resonant surface. In particular, single helicity calculation showed that in the nonlinear limit, there is no saturation mechanism. In our work, further studies of the flow effects on the long wavelength drift wave turbulence are presented. In particular, a three-dimensional, multiple helicity calculation is carried out to study the structure and the saturation mechanism of the modes sitting on a low q resonant surface. Also discussed are the self-consistent effects of both the V_0' and V_0'' flows on the long wavelength drift wave turbulence.

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‡ B.A.Carreras, K.Sidikman, P.H.Diamond, P.W.Terry and L.Garcia (preprint)

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Predictions of α Parameters in Tokamaks with $Q_{DT} \approx 5$*

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The TRANSP code for plasma simulation has recently been extended to calculate parameters of fusion products (T, ^3He, and ^4He) with the same techniques used to calculate fast beam ion parameters. Monte Carlo births of the fusion products are performed using spatially 2D fusion reaction rate data (beam-beam + beam-target + thermonuclear). The fusion products are launched in the (rotating) plasma frame with the appropriate energy. Their orbits, slowing-down, and their heating of the thermal plasma are calculated. The model takes into account non-zero orbit width effects and Larmor radius effects. The fusion products slow down and pitch-angle scatter on thermal plasma species (electrons, ions, and impurities).

We parameterized plasma profiles in several tokamak configurations designed to achieve $Q_{DT} \approx 5$, and used TRANSP to calculate the thermonuclear yields and parameters of the fast fusion α parameters. These parameters include profiles of the density, average energy, slowing down time, heating of electrons and ions, and β_α. We study how these α parameters varied as the shapes and magnitudes of the plasma density and temperatures were varied. The results are useful for indicating the α heating profiles and for calculating α effects such as the TAE and KBM instabilities.

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The Implications of the Generalized Kirchhoff's Law on ECE Emission Diagnostics and the Role of Synchrotron Radiation in Power Balance and Transport

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The effects of mode conversion in an inhomogeneous plasma on cyclotron or synchrotron radiation are embodied in the revised form of Kirchhoff's Law which we call the Generalized Kirchoff's Law (GKL). It has been proved that for each branch, the emission is given by[1]

$$E_k = A_k I_{BB}\,, \qquad k = 1, 2, 3,$$

where E_k is the direct emission on the fast wave branches (in each direction separately) and on the Bernstein branch, and A_k is the absorption coefficient for each branch, and I_{BB} is the black body emission intensity. It is crucial to note that the absorption is not the classical expression, since

$$\begin{aligned} A_1 &= 1 - |T_1|^2 - |R_1|^2 - |C_{13}|^2\,, \\ A_2 &= 1 - |T_2|^2 - |R_2|^2 - |C_{23}|^2\,, \\ A_3 &= 1 - |R_3|^2 - |C_{31}|^2 - |C_{32}|^2\,, \end{aligned}$$

except that $R_1 = 0$, and $T_1 = T_2 = T$, $C_{13} = C_{31}$ and $C_{23} = C_{32}$ by reciprocity[2], where T, R and C are amplitude transmission, reflection and conversion coefficients. The classical expression is $A_1 = A_2 = 1 - T^2 = 1 - e^{-\tau}$. This reduction of the emission due to mode conversion effects is compensated in some cases due to the mode conversion of an incident Bernstein wave adding to the direct emission, but there is still asymmetry between the emission from the high and low field sides unless the absorption is so strong that all mode conversion effects become insignificant. For all cases, the concept of opacity must be revised to include the mode conversion effects. In the strong absorption case, the emission on each branch is black body, and this is common for the second harmonic where most ECE diagnostics operate, so no discrepancy is expected or observed. At $\omega = 3\omega_{ce}$, however, the absorption is not so strong and mode conversion effects are important. For ions, the mode conversion changes are nearly always important, since ion cyclotron harmonic emission is rarely black body and the compensation effects from the incident Bernstein wave are weaker.

For overall synchrotron emission from a plasma, there are contributions from many harmonics, and typically all but the second will be reduced by the effects of the Generalized Kirchhoff's Law. We also note that the Bernstein wave, which emits more strongly than the fast wave branches, carries a nontrivial amount of energy, and ray tracing suggests the distances are over a hundred Larmor radii, so the radiative step size is large compared to the collisional step size, so this will lead to anomalous energy transport. For ions, the step size is typically to the next lower harmonic, so the step size is even larger, although the black body emission is lower at ion cyclotron harmonic frequencies.

We have also calculated for the first time the shape of the source distribution function in a mode conversion layer by relating the source and sink functions through a variational analysis. For the ion source distribution function, the nominally gaussian shape is shifted due to nontrivial mode conversion effects, while the shift in the electron synchrotron case is apparently due more the the relativistic shift and broadening than to mode conversion effects.

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TWO-DIMENSIONAL EDGE PLASMA MODELING (NEWEDGE)

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We have recently developed a fully implicit 2D 2-fluid edge plasma code, NEWEDGE.The utilization of Newton's method on discretized Braginskii fluid equations, plus the addition of mesh sequencing (coarse to fine mesh) to accelerate convergence has shown to be effective. The recent replacement of the analytical Jacobian to numerical Jacobian has shown an increase in the rate of convergence. In order to extend the capability of NEWEDGE to analyze high power devices, we are currently introducing several major revisions.

Parametric studies of convergence and residuals has shown that for high electron and ion boundary temperatures, the convergence is sluggish. A similar trend is observed also for low transport coefficients. During the revision process, a 'simple multigrid like' mesh sequencing was tested and it was observed that for slightly high boundary temperatures, quadratic convergence was obtained. The results indicated that during the mesh sequencing process, the high frequency error which appeared on the fine grid was successfully smoothed on the coarse grid. As an extension, a coarse grid correction scheme is implemented on high boundary temperatures and low transport coefficients problems. The results of convergence and residuals analysis are presented and observations on the numerical results will be addressed.

Another important feature of NEWEDGE is the neutral atom transport model. It is realized that neutral recycling is an important factor to achieve a dense and cool divertor plasma. The application of diffusion models to edge plasma modeling has shown that the ionization profiles can be rather steeped near the plate and can create numerical instability. The equilbrium condition of neutrals with the background plasma near boundaries is also in question .. A proposed remedy is to utilize the First-Flight Corrected Diffusion (FFCD) model.

An earlier study of simulated 1-D edge plasma with FFCD has shown that the ionization profile is less steep than pure difusion model. A simulated 2-D edge plasma with FFCD results will be presented, and implication of its application to NEWEDGE will be addressed.

Nonadiabaticity and toroidal mode coupling in collisional drift waves

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Based on Braginskii's fluid equations, resistive nonadiabatic drift waves in a sheared toroidal domain are investigated. Nonadiabaticity and collisional dissipation equivalently enter the equations. In contrast to conventional approaches the linearized equations are considered with regard to the nonlinear regime, *i. e.*, nonadiabatic layers of modes on neighbouring rational surfaces in overlap. Thus recent computations of drift wave turbulence in slab geometry are taken into account. The use of linearized equations enables numerical study, and may indicate the effect of toroidicity on nonadiabticity for the full nonlinear problem, which still is beyond existing computational capability. The toroidal terms disappear to lowest order in the fluctuation energy equation, suggesting that toroidicity can drive drift waves unstable only by changing the mode structure, *i. e.*, not as a direct source. Furthermore, motivated by the probable turbulent regime, relative phases between modes on different rational surfaces are allowed to vary. It is contrasted with the usual model of constant, vanishing relative phase, which exhibits the drift wave ballooning; the latter requires as a normal mode a common phase of all involved modes. Accordingly, drift wave ballooning may appear as a purely linear effect, which disappears in the nonlinear situation. For the first runs, equal mode structure on different rational surfaces is assumed. Already in the usual linear regime, *i. e.*, nonoverlapping nonadiabatic layers, modes are easily destabilized, since the narrow nonadiabatic layers give rise to large effects in toroidal coupling terms involving the corresponding radial derivative (recall that linear slab modes are always stable).

THE TEMPERATURE DEPENDENCE OF LHCD EFFICIENCY

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Experiments on JT-60 [1] and JET [2] show that the LHCD efficiency has a strong dependence on the volume averaged electron temperature. According to the simplest theories, the efficiency should be nearly independent of temperature (since the collision frequency of fast electrons is a function of their energy and not the bulk plasma temperature). However, it is widely recognized that the launched spectrum in LHCD is quite different from the one that is absorbed in the plasma and that toroidal effects on the wave propagation can result in the filling of the "spectral gap". We have shown (using ray tracing codes and Hamiltonian chaos theory) that in the parameter regime of interest the ray trajectories are in fact stochastic. This leads to a diffusion of the wave energy from low k-parallel (where it is launched) to high k-parallel (where it is absorbed by electron Landau damping) [3]. The width of the spectrum inside the plasma is a function of temperature and therefore one observes a temperature dependence in the current drive efficiency. In addition, non-resonant losses of wave energy, due to collisional effects and lossy reflections near the plasma edge, are greatly enhanced at low temperatures, since it takes longer for the wave energy to diffuse to high k-parallel (i.e. the rays make many more passes and suffer greater non-resonant losses). We have included these effects in a simple model that gives reasonably good agreement with the experimental results. (Note, the 1-d velocity space model, where the spectral gap is filled to approximately $3v_e$ and the quasilinear diffusion coefficient is large, yields a temperature dependence of the efficiency that is too weak in comparison with the experimental results.) Our model also predicts two new effects which should be possible to verify during low temperature LHCD experiments: (i) a strong exponential decay of the efficiency below some critical temperature when non-resonant losses of wave energy become large; and (ii) a KAM barrier in k-parallel, which can prevent the launched spectrum from coupling to the electron bulk. Results for JT-60 and Tore Supra parameters are discussed.

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PONDEROMOTIVE CURRENT DRIVE BY ALFVÉN-ION CYCLOTRON WAVES

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It has been suggested[1,2] that Alfvén waves can drive current through the creation of a dynamo electromotive force in the plasma. Within the realm of MHD the dynamo effect is proportional to the resistivity and therefore does not lead to large currents for the reactor range of parameters. In the search of a larger effect one can generalize this approach to allow for non-MHD phenomena like Hall resistivity, thermal and kinetic effects, etc. This can be done by employing the ponderomotive force formalism[3,4] to derive the time-averaged two-fluid theory from which the modified Ohm's law is deduced[5]. In the zero resistivity limit it is found that the dynamo field parallel to the magnetic field is a gradient of a scalar, i.e., it does not lead to a net electromotive force, even with the Hall term included. However, the incorporation of thermal effects causes the appearance of a new ponderomotive force due to the spatial dispersion which can lead to a non-conservative parallel dynamo field. We discuss this effect and the role of resonant particles and anisotropic pressure. We calculate the resulting current for the parameter range of current drive experiments on Phaedrus-T.

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Physics Basis for Advanced Tokamaks*

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There is a considerable interest in advanced tokamak configurations having both high beta and high boot strap fraction, and with plasma profiles that are both compatible with complete MHD stability and with practical current drive methods. We have carried out a systematic design and optimization study which illustrates the properties and constraints imposed by these configurations. We discuss the applicability of advanced tokamaks for fusion reactors and for more near term steady state experiments.

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EFFECT OF MAGNETIC FLUCTUATIONS ON THE LOWER HYBRID WAVE PROPAGATION IN TOKAMAKS

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Abstract

Recently, lower hybrid (LH) waves have been utilized for electron and ion plasma heating, to sustain and rampup toroidal plasma current, and to stabilize sawteeth. However, LH wave penetration is expected to be limited to $r/a \geq 0.5$ in a reactor due to the relatively high central electron densities and temperatures. LH current drive may also be useful in current profile control. Hence it is important to consider the effects of both density and magnetic fluctuations on LH wave propagation.

Here, we extend the work of Bonoli & Ott[1] by deriving a wave kinetic equation for lower hybrid wave propagation that includes the effects of both magnetic and density fluctuations. This integral equation is then solved by Monte Carlo procedures for an Alcator-C Mod toroidal tokamak. It is shown that even for magnetic/density fluctuation levels on the order of 10^{-4}, there are significant magnetic fluctuation effects on the wave power deposition into the plasma. These effects are quite pronounced if the magnetic fluctuations are peaked within the plasma.

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SHERWOOD THEORY MEETING 1992

MDI: Mathematica Database Interface for the MFE Database*

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We describe a new interface for the MFE Database[1] which uses *Mathematica®* as a front end. MDI is a *Mathematica* package that defines a basic set of MFE database access functions. The package will also accept standard SQL queries. Each function returns *Mathematica* style lists, which can then be manipulated with any of the *Mathematica* functions. MDI also provides some utility functions for plotting and analyzing the data. The MDI package essentially makes the MFE Database an extension of *Mathematica* . The user may use any of the many *Mathematica* front-ends including telnet, X-Windows, or a notebook. The MDI.m package may be obtained by anonymous FTP from the MFE Database site or by use of netmfe[2], an E-mail database interface.

MDI is a example of distributed computing. Behind the user interface, MDI calls an RPC[3] client program that communicates with an RPC server on the MFE Database computer. It relies on the network communication capabilities of *Mathematica* to connect the user to a workstation running the *Mathematica* kernel. The *Mathematica* kernel is then connect to the MFE Database host workstation by a client/server pair of RPC processes. If the *Mathematica* kernel is to be run on the users machine, the RPC client program must also be obtained and installed.

The MDI RPC server is also available for users who would like to provide their own client software. The server returns ASCII tables from standard queries and may be accessed and processed by any program on the internet that has access to RPC services.

* Supported by USDOE Grant DE-FG05-88ER53266

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Nonlinear Evolution of Alpha Particle Driven Alfven Turbulence And Anomalous Alpha Transport*

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Recent accumulating experimental evidence[1,2] of bursts of Alfven fluctuations in tokamak with energetic ion injection has led us to investigate fusion alpha particle driven Alfven turbulence and anomalous alpha transport. The investigation is in a slab geometry, and based on a set of coupled nonlinear equations that self-consistently describe the temporal-spatial evolutions of the alpha particle density $n^{\alpha}(r,t)$, and turbulence spectrum $|\tilde{\phi}|^2_k(t)$ in the presence of a fusion alpha particle source $S^f(r,t)$:

$$\frac{\partial}{\partial t}n^{\alpha}(r,t) + \frac{\partial}{\partial r}\Gamma^{\alpha}(r,t) = S^f(r,t)$$

$$\frac{\partial}{\partial t}|\tilde{\phi}|^2_k(t) = 2(\gamma^l_{\alpha} + \gamma^l_e + \gamma^{nl}_i)|\tilde{\phi}|^2_k(t)$$

where, $\Gamma^{\alpha}(r,t)$ is the Quasi-Linear α particle flux which depends on both the α particle density $n^{\alpha}(r,t)$ and turbulence fluctuation spectrum $|\tilde{\phi}|^2_k(t)$, γ^l_{α} is the linear α particle growth rate, γ^l_e is the linear electron Landau damping rate, and γ^{nl}_i is the nonlinear growth rate due to bulk ion Compton scattering. The Alfven turbulence is driven by the expansion free energy in the α density gradient. The turbulence excited induces anomalous α transport. The anomalous α transport will modify the α particle density profile, and compete with bulk ion Compton scattering to regulate the nonlinear evolution of Alfven turbulence. These coupled nonlinear equations will be solved numerically. Conditions for the possible nonmonotonic temporal behavior of $n^{\alpha}(r,t)$ will be explored.

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Empirical Spectral Codes for Tokamak Turbulence*

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Novel techniques are developed for the analysis and calculation of tokamak turbulence. Principal component analysis (PCA) is performed on output data from a conventional simulation code to obtain efficient representations of the spatial and temporal variations in the fluctuations of potential, parallel flow velocity, and electron temperature. The spatial patterns found by PCA form a basis set of empirical orthogonal functions that are used in a Galerkin procedure to develop an empirical spectral code for the turbulence. The time-evolution equations in such a code are similar in form to the equations in a conventional spectral code. The number of equations can be much smaller, and more efficient simulations are possible. Empirical-spectral equations have been formulated and coded for an important class of systems that are described by partial differential equations containing source/sink terms, linear terms, and quadratically nonlinear terms. Our techniques are applied to simple, quadratically nonlinear, fluid models of ion-temperature-gradient turbulence in sheared-slab geometry. Initial results are for the zero-Larmor-radius limit on a two-dimensional (radial and poloidal) domain. Empirical-spectral-code runs reproduce the statistics and temporal behavior seen in conventional simulations if we use additional damping to suppress the shortest-wavelength basis functions. Robustness of the basis set with respect to variations of physical parameters is discussed.

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A Normal Form Theory of Pairwise Linear Mode Conversion†

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We consider the problem of linear mode conversion, which arises when applying WKB methods to multi-component wave equations in inhomogeneous media. Several methods[1–4] have been developed for treating certain classes of mode conversion problems, primarily in one-dimensional (slab) geometries; however, to our knowledge there has been no systematic analysis of the general mode conversion problem.

We therefore address the general mode conversion problem for two coupled waves in an arbitrary number of dimensions. Our analysis, motivated by Friedland[2] and Kaufman and Friedland,[3] is in the spirit of catastrophe theory; we consider a linear approximation to the wave equations in the mode conversion region, and then look for the various normal forms into which these approximate equations can be brought using certain transformations of the wave fields. We find that when this linear analysis is valid, there are just four normal forms which the wave equations may take, all of which can be solved analytically. The simplest normal form is the one which has appeared most frequently in the plasma literature,[1–3] while the others seem to be unknown outside of the chemical literature.[5] Preliminary results have been reported in Ref. 6.

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Electromagnetic Effects in Convective Cell Fluctuations and Diffusion

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Abstract

Renormalized statistical theory of low-frequency hydrodynamic fluctuations in magnetized plasmas is applied for the general case of electromagnetic fluctuations. Stationary spectra of electromagnetic field thermal fluctuations are derived with regard to nonlinear interaction between potential and magnetic field excitations. The well known results of the potential theories [1,2] are recovered only in the limit of cold electrons, $T_e << T_i$, or for plasmas with very low pressure, $\beta_i \equiv 8\pi n_0 T_i/B_0^2 << m_e/m_i$. Substantial broadening of the convective cell potential spectrum and suppression of convective cell diffusion due to magnetic field fluctuations, are predicted, when $T_e \sim T_i$, $\beta_i \gtrsim m_e/m_i$: $\nu_N \sim \nu_{pot}(T_e/T_i)^2(\nu_{pot}/2\nu_m) >> \nu_{pot}$, $D \sim D_{pot}(\nu_{pot}/\nu_N) << D_{pot}$. Here ν_N is a renormalized coefficient of kinematic viscosity, which governs the width of the potential spectrum, D is a test-particle diffusion coefficient, ν_{pot} and D_{pot} are the predictions of potential theories [1,2], ν_m is a linear magnetic viscosity.

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Computational Study of the Interplay of E×B and Polarization Drift Nonlinearities in Drift Wave Turbulence

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Recent development of core fluctuation diagnostics and a re-examination of saturated trapped ion mode turbulence have rekindled interest in long wavelength fluctuations in the context of the tokamak core. Here, we present the results of a computational study of 2-D dissipative trapped ion convective cell turbulence modelled by a one-fluid Kadomtsev-Pogutse equation. We focus on robust nonlinear processes that are governed by the ExB and polarization drift nonlinearities generic to drift wave turbulence, including the direction of spectral energy transfer and its relation to dynamical invariants, the locality and isotropy of transfer in wavenumber space, and the frequency spectrum.

The ExB and polarization drift nonlinearities are different in character, and the rich phenomenology of their interplay in the transfer process is a central theme of this work. The ExB nonlinearity, which dominates in a long wavelength subrange, was found (when acting alone) to transfer energy to small scales, consistent with its conservation of a single quadratic invariant (energy). By direct measurement of the rate and direction of nonlinear transfer, it was also found that spectral energy transfer of the ExB nonlinearity is highly nonlocal and anisotropic. Transfer in the k_y direction readily spans the entire spectrum in a single correlation time, thus departing dramatically from the canonical self-similar cascade process typically envisioned for turbulence. At the same time the transfer in the k_x direction is local, in closer conformity with the idea of a cascade. By contrast, the polarization drift nonlinearity, acting alone, transfers energy to low k, in keeping with its conservation of a second quadratic invariant, the enstrophy (mean square vorticity). Direct measurement of the nonlinear transfer showed it to be both predominantly local and isotropic.

With both nonlinearities present, subranges were found in which the transfer was virtually indistinguishable from the transfer of the dominant nonlinearity when acting alone. Enstrophy production was found to provide a good measure of the relative strengths of the nonlinearities. When the ExB nonlinearity dominates, enstrophy production is significant and occurs on the nonlinear interaction time scale. When the polarization nonlinearity dominates, enstrophy production is weak and occurs over many nonlinear interaction time scales. A third subrange, in which neither nonlinearity plays a dominant role and enstrophy production is moderate, was also studied. Here, the transfer has a large nonlocal component yet is relatively isotropic.

A novel and potentially important aspect of the interplay between the two nonlinearities was observed in the frequency spectra of individual modes. In the regime where both nonlinearities are comparable, a large shift of the frequency spectrum peak is observed. For shorter wavelength modes, the shift is to higher frequency and can be as large as 3 - 5 times the diamagnetic frequency. If either nonlinearity is absent, or contributes only weakly to the transfer dynamics, the shift is small.

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Abstract submitted for the International Sherwood Controlled Fusion Theory Conference, April 6-8, 1992

Effect of Bootstrap Current Modified Profiles on Ideal MHD Stability Limits for Long Pulse, High Poloidal Beta Equilibria in TFTR†

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During the 1992 run, high poloidal beta plasmas were created in TFTR with neutral beam heating pulse lengths of up to four seconds in duration. The heating power and Troyon normalized beta were intentionally restricted to modest levels in order to study the plasma behavior over long timescales. The total injected beam power was in the range 7 - 10 MW with the majority of shots having balanced injection. The discharges were created with I_p decreased, or ramped down, before the start of neutral beam injection. The plasma current was in the range 1.0 - 0.85 MA before the I_p ramp-down and 0.6 - 0.4 MA during beam injection. Values of $\varepsilon\beta_{p\ dia} \equiv 2\mu_o\varepsilon<p_\perp>/<<B_p>>^2$ as large as 1.4 were created during the initial portion of the low current discharges. Both slow and fast β decays were observed as the plasmas evolved, and $\varepsilon\beta_{p\ dia}$ settled to a value in the range 0.4 - 0.5 by the end of the beam pulse. The observed collapses in β correspond to the onset of MHD activity. The measured surface voltage is small in the high β_p plasmas, and discharge modelling using the TRANSP[1] code indicates that between 40 - 65% of the plasma current is driven by the bootstrap current and that between 60 - 80% of the current is driven non-inductively. The bootstrap component dominates the outer half of the current profile and in some cases supplies all of the current in this region.

The ideal MHD stability of these equilibria is examined to determine the effect of the equilibrium profile evolution that occurs in these discharges. Since the high β_p plasmas are initiated by a ramping down of I_p, and last sufficiently long to allow the bootstrap current to develop, the current profile takes on a variety of shapes throughout the lifetime of the discharge. In particular, the I_p ramp-down creates a peaked current profile[2], and the evolution of the bootstrap current forces the profile to become more broad. Both high and low-n number ideal MHD stability limits will be identified for the evolving equilibria, as well as the location of the modelled experimental equilibria with respect to these limits. Previous analysis of discharges with I_p ramp-down showed a substantial improvement of the low-n mode beta limit. Peaking of the current profile was shown to be an important factor in this improvement. In the present analysis, attention will be placed on the alteration of the plasma stability limits caused by the bootstrap driven broadening of the current profile.

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Edge Turbulence Scaling with Shear Flow*

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A formula relating turbulence levels with arbitrary shear flow is derived. When the diffusion coefficient is made a functional of the corresponding turbulence level, it is found that: (1) Shaing et al.'s results[1] follow in the small shear limit, (2) the (-2/3) scaling[2] found by Biglari et al., is correct only if the diffusion coefficient is independent of the turbulence level; (3) the turbulence suppression mainly pertains in the moderate shear flow regime; and (4) the shear flow suppression becomes much more (less) effective for flattened (steep) equilibrium gradient.

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STABILITY THEORY FORMULATED IN TERMS OF A SCALAR REPRESENTATION

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In the first part of this work, a representation of MHD in terms of stream functions and potentials, proposed earlier, is employed to describe "saturated" instabilities by means of bifurcation theory. More generally, slowly evolving states resulting from a saturated MHD instability may be described in this way under certain conditions.

In the second part of this work, a representation of guiding center motion is formulated, using stream functions and potentials in analogy with the above representation of MHD. In this way it is possible to describe particle motion in toroidal magnetic fields with islands and stochastic regions.

Finally, we discuss the description of the interaction of particle motion with macroscopic MHD motion in the frame of a theory using the above representations.

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Mathematica Approach to Neoclassical Theory*

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A *Mathematica*[1] code (MANT) is being written to determine complete neoclassical transport coefficients using Hirshman and Sigmar's moment method[2]. For given experimental data inputs such as $n_a(r)$, $T_a(r)$, $L_n(r)$, $L_T(r)$ and magnetic equilibrium data, etc., even in a multi-species and mixed multi-collisionality plasma, this code can output complete neoclassical transport coefficients such as rotation coefficients, Bootstrap current coefficients, complete diagonal and off-diagonal radial transport coefficients for all species. The results of this code will be used to discuss the following topics:

- Comparison with previous neoclassical theories
- Toroidal and poloidal rotation velocities of all ion species in a multi-species plasma
- Complete bootstrap current and ohmic current
- Diagonal and Off-diagonal radial transport fluxes and Onsager symmetry
- Limitations of this code and future implementations
- Automatic link between this code and transport analysis code (e.g., ENERGY code in GA)

*. This research was supported by USDOE through subcontract from General Atomics.

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MAGNETIC TOPOLOGY TRANSITIONS IN COLLISIONLESS PLASMAS

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Processes capable of producing new magnetic field topologies (so-called reconnection), in collisionless plasmas are shown[1] to develop with relatively high growth rates and to be suitable to explain the so-called "crash" of high plasma temperature regimes that are observed in well confined plasmas, after periodic reconnection events (so-called "sawtooth oscillations") attributed to the effect of the collisional plasma resistivity have been suppressed by the injection of a high energy particle population. Two models for the nonlinear development[2] of the relevant instability are proposed. The relevance of these processes to space physics phenomena is pointed out.

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High β Axisymmetric D-^{3}He Reactor with Internal Levitated Coil

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The physical concept of a D-^{3}He reactor based on the spherator-like toroidal field free magnetic system with an internal levitated coil (ring) is discussed. An axisymmetric magnetic configuration is formed by the superposition of vertical mirror field produced by external coils and the internal ring field which is opposite to the mirror field. The resulting magnetic configuration is similar to FRC. Contrary to [1] the magnetic separatrix is inside the vacuum chamber and plays the role of a natural diverter.

To analyze the concept we discuss the following problems: equilibrium and stability, internal ring structure, parameters estimates, neutron and radiation fluxes on the ring surface. The main attention is focused on the relevant mechanism of the plasma thermal flux to the ring.

Taking into consideration both engineering and physical aspects we have estimated the key reactor parameters as follows:

- major and minor internal ring radii are $R_R = 4\ m$ and $a = 0.8\ m$ respectively (including neutron and thermal shield);
- total super conducting ring current $I_R = 23\ MA$, magnetic field at the ring surface $B_R = 6\ T$ and at the axis in the midplane $B_0 = 2.9\ T$;
- the maximum density $n = 4 \cdot 10^{14}\ cm^{-3}$ and temperature $T = 50\ kev$;
- the volume everaged hot ignited zone β is about 5;
- the total reactor fusion power is about *1 GW*, the total bremsstrahlung radiation power is about *200 MW*, the total cyclotron radiation power is about *80 MW*;
- the over-all energy flux density to the ring is about $0.8\ MW/m^2$. In this case the equilibrium black body radiation temperature of the ring surface has to be *1900 K*.

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MHD computation of effects of feedback and mode rotation on RFP tearing modes

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We have demonstrated numerically that application of feedback signals locked in phase with a few internally resonant tearing modes can lower fluctuations and loop voltage in the Reversed Field Pinch (RFP) with a resistive shell.[1,2] Our first feedback schemes modeled perfectly conducting helical coils which held the edge radial magnetic field $B_r(a)=0$ for targeted modes of given (m,n). We generalize these investigations by testing feedback schemes with nonzero phase shifts between the applied $B_r(a)$ and the plasma signal, and with variable nonzero $B_r(a)$.

In one set of tests, $B_r(a)$ is held proportional to $B_r(r_s)$ at the resonant surface r_s of the targeted mode, to flatten the driving term $\Delta' = (\psi'_+ - \psi'_-)/\psi(r_s)$. This scheme effectively stabilized tearing modes in tokamak plasmas[3] , and can lead to linear saturation of RFP tearing modes. Initial results suggest that, nonlinearly, there is at best a narrow range of parameters for which this scheme does not induce the phase-flip instability in the RFP, perhaps because the targeted modes are resonant much nearer the plasma axis than in the tokamak case. In another set of tests, feedback coils are effectively rotated with respect to the plasma to induce or suppress mode rotation. It has been experimentally observed[4,5] that RFP tearing mode growth is suppressed by mode rotation and enhanced by modes locking to field errors. These situations are investigated numerically and results are compared with experimental observations. Threshholds are sought for minimum mode rotations and maximum feedback phase shifts which suppress tearing mode growth in the absence of a conducting shell.

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BOOTSTRAP DEPENDENCE ON PROFILE PARAMETERS AND J_{BS} ALIGNMENT*

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The bootstrap fraction, I_{bs}/I_p, and the shape of the bootstrap current density, J_{bs}, can depend sensitively on the shape of plasma profiles. It is useful to identify possible modes of operation of tokamaks that make maximum use of the bootstrap current. To aid this identification we derive an expression for the bootstrap fraction of the form

$$I_{bs}/I_p = \varepsilon^{1/2}\beta p\ C_{bs}\,(\alpha_n, \alpha_T; \alpha_J, Z_{eff}, \varepsilon)$$

which depends explicitly on the profile peakedness parameters α_n, α_T and α_J. We employ a simple characterization of "desirable" bootstrap current density shape based on the radial location, x_t, of the turning point maximum of J_{bs}. By superimposing contours of C_{bs} with those of x_t, we are able to identify regions of profile parameter space which maximize I_{bs}/I_p with "desirable" J_{bs}.

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Vortex-Wave Dynamics in an Inhomogeneous Magnetized Plasma*

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A self-consistent theory describing vortex-wave dynamics in a magnetized plasma has been formulated based on the Hasegawa-Mima equation by extending the modulated point vortex model[1,2] to include the vortex-wave interactions. Each vortex is advected by the other vortices and waves. When the vortex motion in the direction perpendicular to the diamagnetic direction changes in time, the vortex emits or absorbs waves, and at the same time the magnitude of its vorticity changes. Thus, energy and enstrophy are shown to be conserved in contrast with the previous point vortex description. Dynamical behaviors of vortices under the interaction with waves are numerically studied. A vortex-pair is shown to be subject to chaotic motion resulting in diffusion in a radial direction and confinement in the diamagnetic direction under the action of a linear drift wave.

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Kinetic theory of toroidicity-induced Alfvén eigenmodes

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An analytic kinetic description of the toroidicity-induced Alfvén eigenmode (TAE) is presented. The theory includes electron parallel dynamics non-perturbatively, an effect which is found to strongly influence the character and damping of the TAE - contrary to previous theoretical predictions. We use a parallel conductivity model that includes collisionless (Landau) damping on the passing electrons and collisional damping on both trapped and passing electrons. Together, these mechanisms damp the TAE more strongly than previously expected, and may explain recent experimental measurements of the TAE damping coefficient. Results are compared with other models for damping of the TAE. In addition, the theory predicts a "kinetic" TAE, whose eigenfrequency is just outside the gap, whose existence depends on finite conductivity, and which is related to the kinetic Alfvén wave.

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Generation of Toroidal Convective Cells in the Tokamak Edge[1]

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Poloidially asymmetric transport for which the transport time scale is comparable to the sound transit time, can lead to large flows parallel to the magnetic field. These flows can have steep cross field gradients, which are unstable to the electrostatic parallel velocity shear instability. For CCT, which has a weak toroidal magnetic field B_ϕ, axisymmetric modes $(\partial/\partial\phi = 0)$ are unstable, while in machines such as TEXT and DIIID which have larger values of B_ϕ, axisymmetric modes are stable. A 2D fluid code has been developed to study the nonlinear evolution of these modes in an axisymmetric toroidal geometry. The associated turbulence that we find shows development of toroidal convective cells with large (order unity) density and potential fluctuations. These fluctuations can drive both perpendicular and parallel shear flows which can affect the fluctuations. We will examine the role of magnetic pumping on the development of these shear flows and on the nonlinear evolution of the convection cells. The relevance of our calculations to edge turbulence in CCT, TEXT, and other tokamaks will be discussed.

[1]Work Supported by U.S. D.O.E.

Impurity Effects on Toroidal ITG Modes

Circular vs. Elliptical Plasma Crossections *

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The linear stability theory of toroidal ion temperature gradient (ITG) modes is studied for plasmas with circular and elliptical cross sections. These drift-like modes are driven unstable by the combination of a free energy source (the ion temperature gradient) and perpendicular compressibility of the ion $\mathbf{E} \times \mathbf{B}$ motion. When the mode has odd parity,[1] it is driven by the ions alone, and when it has even parity, it can be driven unstable by the precession drift of trapped elections. In the latter case it has been known under the appellation of "ubiquitous mode". Since it is now known that dilution of the main ion concentration (the source of free energy) by the appearance of impurities can raise the threshold of ITG modes (local theory) of both the toroidal and slab branches, the fully nonlocal linear theory is examined with a second ion species included. The dependence of the stability threshold and of the growth rate (once the threshold is crossed) on main plasma parameters (e.g., ellipticity, impurity concentration,...) and mode characteristics (e.g., toroidal mode number, coupling to the sound wave,...) will be discussed.

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Anomalous Kinetics of Incomplete Chaos*

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Large scale structures in the phase space of a particle influence intermittency phenomena in dynamics and incomplete mixing of orbits. In the example of particle motion in a wave packet, it is shown how the breakdown of quasilinear theory could appear and how its breaking correlates to a pattern of the phase space. Existence of the pattern due to resonances produce intermittency in the form of particle trappings and flights. Such behavior can be described using non-gaussian random walk processes which define an anomalous transport for the particle diffusional process.

A new equation of transport is derived instead of the quasilinear equation which is of the Fokker-Planck-Kolmogorov type. The main property of the new equation is that it describes fractal kinetics. This means that random wandering is performed in the fractal space-time situation. Physical interpretation of this phenomenon is given. The final exponent of time behavior of the mean displacement is obtained. Its connection to local phase space properties is discussed.

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Nonlinear Drift Wave Structures in a Sheared Magnetic Field*

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Nonlinear coherent structures governed by the coupled drift wave-ion acoustic mode equations in nonuniform plasmas with sheared magnetic fields are studied analytically and numerically.

It is shown that the magnetic shear combines with the nonlinear convective derivatives in both the vorticity (or charge neutrality) equation and the parallel ion momentum transport equation to produce a binding force proportional to $S^2\varphi^3/u^4$ giving a new analytic vortex structure.[1] Here $S = L_n/L_s$ is the magnetic shear, φ the electrostatic potential and u the poloidal speed of the coherent structure. The nonlinear eigenvalue problem shows the existence of a banded spectrum in the shear versus amplitude plane. Both the shear and the amplitude must exceed critical values for the existence of these coherent structures. The critical values are reasonable for drift turbulence just above the mixing-length amplitude as is often observed in tokamaks. The structures are related to the Meiss-Horton perturbative vortex solutions[2] and in the small amplitude limit reduce to the shear-damped drift wave eigenmodes.

Numerical simulations are given of the 2D equations and used to show the soliton-like robustness of the coherent structures. As in the $S = L_n/L_s = 0$ case, however, the dipolar structure is shown to be broken into monopoles[3] when there is an appreciable gradient of the drift velocity $v_d = cT_e/eBL_N$ across the diameter of the vortex.

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Nonlinear skin phenomena in (almost) collisionless short-duration plasmas

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Progress is reported on the understanding of fast magnetic evolution in plasmas of low collisionality. When time-scales are short, the ions are essentially immobile and the so-called electron magneto-hydrodynamics (EMHD)[1] equations most aptly describe the plasma. In plasmas in which the characteristic length is smaller than the ion skin depth, density nonuniformities[2] or magnetic field curvature[3] can result in shock like fast magnetic field penetration. Large deviations from the frozen-in law and large energy dissipation occur even if the collisionality is small[4]. The two-dimensional power flow in a plasma that conducts current between two electrodes results in energy dissipation both in the bulk of the plasma and near the electrodes[5]. In the case that the current-carrying electrons move from a high density region to a low-density region the magnetic field does not penetrate into the plasma. Moreover, in this case, if the plasma initially is permeated by the field, then that field can be spontaneously expelled[3]. Recently, the strictly collisionless case has been studied. Fast magnetic field penetration has been demonstrated due to electron inertia, with no energy dissipation in the bulk of the plasma[6,7].

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The Theory of Nearly Incompressible Magnetofluid-Dynamics

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The importance of turbulent density fluctuations in plasma fusion devices is widely recognized[1] yet a detailed theoretical description for compressible MHD turbulence has proved elusive. However, observations of Kolmogorov-like density spectra in turbulent plasmas such as the solar wind have been known for some time, and have spurred the development of theoretical descriptions to explain these observations[2]. By considering the magnetofluid limit in the low Mach number limit (defined appropriately), we have developed a model (Nearly Incompressible MHD—NI MHD) which describes weakly compressible corrections to an incompressible MHD description. It is shown that the correct form of the incompressible MHD equations depends critically on the magnitude of the plasma beta. The NI MHD equations bear some relationship to the well-known equations of Reduced MHD (RMHD)[3] except that turbulent density fluctuations represent an integral part of the NI formulation. NI MHD provides a relatively tractable approach to the investigation of compressible effects in a turbulent plasma whenever either RMHD or incompressible MHD are thought to provide a reasonable description for the leading order fluctuations. An overview of NI MHD is presented and its relationship to previously developed incompressible turbulent descriptions elucidated.

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The Effects of Finite-β and of Radial Boundary Conditions in Gyrofluid Equations.

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The slab electrostatic gyrofluid equations and their computational solution are described in more detail in Ref. 1 and in an accompanying poster at this conference (Ref. 2). Here we demonstrate the extension of these equations to "finite-β" electromagnetic perturbations ($\delta A_{\parallel} \neq 0$). Kadomtsev and Pogutse[3] derived a similar set of equations which included an approximate fluid model of kinetic effects such as Landau damping. Our models have a number of improvements and extensions. Our approach also indicates that in the phase-mixing damping rate $\sim |k_{\parallel}|v_t$, one should use a $k_{\parallel}$ defined along the total magnetic field $\vec{B}_0 + \vec{B}_1$, leading to nonlinear effects in the phase-mixing. Our equations also have some similarities to the recent work of Chang and Callen[4], and of Brizard[5], while providing several extensions.

In addition to these analytic derivations of finite-β equations, we also consider the effects of various radial boundary conditions on nonlinear numerical simulations of ITG-driven turbulence (in the electrostatic limit). One of the key issues is whether the $k_y = 0$, $k_z = 0$ component of the perturbed pressure, $p_{0,0}(x,t)$, is allowed to undergo "quasilinear" relaxation and thus eventually cancel the background pressure gradient, or whether the background pressure gradient is maintained. The background pressure gradient can be maintained either by setting $p_{0,0} = 0$, or by using periodic radial boundary conditions so that any heat flux which goes out one side of the box comes back in the other side. Periodic radial boundary conditions require special treatment in the presence of a sheared magnetic field, such as the method proposed by Cowley et.al.[6] employing a "twisted-eddy" (or nonlinear ballooning) coordinate transformation. We will also compare our gyrofluid simulations with other published numerical simulations and with experimental data from TFTR.

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Nonlinear Gyrofluid Simulation and Analysis: ITG Turbulence

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We have developed a set of nonlinear, collisionless gyrofluid equations useful for numerical investigation of low frequency plasma turbulence in a slab geometry with magnetic shear. The ion equations are obtained by taking moments of the nonlinear gyrokinetic equation directly, closing the hierarchy with a collisionless phase mixing model[1] (which includes Landau damping) extended to include FLR effects.[2] These equations determine the evolution of $n_i, u_{\|i}, T_{\|i}$ and $T_{\perp i}$, plus $q_{\|i}$ and $q_{\perp i}$ if greater accuracy is desired. We have recently upgraded our code to include nonadiabatic electrons, using the $k_\perp \rho_e \to 0$ limit of the gyrofluid equations.

As a partial check of our numerical code, we present several linear benchmarks with examples from the extensive ITG literature, showing that we recover with very good accuracy the linear ITG mode properties in the "kinetic" regime, even in the presence of magnetic shear. Our phase mixing models for $2n$ fluid moments (including FLR effects) correspond to n-pole approximations of the plasma dispersion function. This accuracy allows us, for example, to reproduce the kinetic η_{crit} *vs.* $k_\perp \rho$ curve exactly. We obtain this agreement at the price of some complexity in the FLR model; hence, we also present a simpler, Padé FLR model easily implemented with standard finite difference algorithms.

We also extend analytic tests of these fluid equations to the nonlinear regime, demonstrating that they describe nonlinear ion Compton scattering. It appears that velocity space integrals which include the linear propagator $(\omega - k_\| v_\|)^{-1}$ in a kinetic weak turbulence analysis are generally replaced by n-pole approximations in our fluid approach.

We may incorporate the linear sheared velocity flow model of Ref. 3 easily into our fluid formalism, extending their results to the "kinetic" regime. Our ordering automatically includes sheared flows self-generated by nonlinear processes. Thus, we show that our model is immediately suitable for the study of ITG turbulence in the presence of sheared velocity flows.

Finally, we have begun 3D nonlinear numerical simulations of ITG turbulence to determine the scaling of χ_i with η_i, L_n/L_s, box size, etc. Progress from these nonlinear simulations will be presented.

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Tokamak Scrape-Off Layer Simulations Using the Fully Implicit LEDGE Code *

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We have developed a fully implicit 2-D fluid code called LEDGE to model the scrape-off layer of a tokamak. In addition to the usual assumptions used in this type of calculation[1] of classical transport along the magnetic field and anomalous transport across the field, we have included classical cross-field drifts. The neutral gas generated by recycling from divertor plates is modeled by a one-group diffusion equation. The code can be run in either the time-dependent mode using the method-of-lines with a Krylov iteration technique, or in a steady-state mode using a direct Newton iteration. We will compare code performance using sparse matrix solvers with that of a banded matrix solver. We use the time-dependent mode to model transient behavior such as ELMS by modulating the anomalous diffusion coefficients. The time-dependent response gives another dimension in which to compare modeling with experimental data. We also investigate the consequences of a theory-based diffusion coefficient obtained from an analysis of the electron temperature-gradient mode in the scrape-off layer[2]. Calculations will be presented for both DIII-D and ITER parameters.

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Influence of Various Physics Phenomena on Fast-Wave Current Drive Efficiency in Advanced Tokamaks*

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PICES is a two-and-one-half-dimensional (2 1/2-D), full-wave code for modeling ion cyclotron resonance heating (ICRH) and current drive based on the poloidal mode expansion method and the reduced-order expansion. By 2 1/2-D we mean that 3-D wave fields are calculated in axisymmetric geometry (2-D solution domain – r, θ), while the correct toroidal dependence of the antenna source currents is obtained from a 2-D (r, ϕ) recessed antenna code. The model correctly includes the poloidal and toroidal structure of the antennas, the modification of the $k_{||}$ spectrum due to the poloidal magnetic field, and a nonperturbative solution for $E_{||}$. A semianalytic model for current drive, including trapped electron effects, is employed. The code has been used extensively to model DIII-D, ITER, TPX, and other tokamaks.

In this paper we will analyze the influence of the relevant physics phenomena (which are not necessarily independent) on current drive performance. Such phenomena include diffraction and other nongeometrical optics processes, $k_{||}$ modification, single-pass absorption, and antenna characteristics, such as poloidal extent and poloidal location. Comparison will be made to results from ray tracing.

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Finite-beta Gyrokinetic Plasma Simulation using the Canonical Momentum Formulation*

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A one-dimensional, finite-beta, gyrokinetic code has been developed using position x and canonical parallel momentum $p_{\|}$ as the particle coordinates in phase space. It has been suggested that the choice of $p_{\|}$ as an independent variable offers several advantages over the parallel velocity $v_{\|}$, such as the elimination of the need to calculate the induction electric field explicitly using a generalized Ohm's law.[1] The Vlasov-Maxwell system of equations which is solved in our new code has been derived in a simple manner directly from its original form in $(x, v_{\|})$ phase space. This derivation illustrates how the computational advantages of the $(x, p_{\|})$ system arise. The issues of numerical noise, adiabatic cutoffs, and implementation of partially linearized algorithms[2] and fully nonlinear weighting schemes[3] are also discussed. Simulations of the kinetic shear-Alfvén wave by the new code will be compared to results obtained previously with a one-dimensional, finite-beta, gyrokinetic code written in the conventional $(x, v_{\|})$ coordinates.[4]

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Ion Cyclotron Heating with Lower Hybrid Waves

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ABSTRACT

A proposed ion cyclotron heating scheme uses the nonlinear interaction of two lower hybrid (LH) frequency waves. The two LH waves are staggered in frequency by the ion cyclotron frequency, i.e. $\omega_{LH1} - \omega_{LH2} = \omega_{ci}$. The validity of this approach is demonstrated with a δf simulation linearized about an equilibrium that accounts for the two LH pump waves. The simulation shows that for relatively modest device levels $(eE_\perp/(m_e v_{te}\omega_{pe}) = 0.1)$, large growth rates $(\gamma \sim 0.1\omega_{ci})$ for the excited ion cyclotron wave are obtained. The excited wave can lead to ion cyclotron heating but without the problems associated with ion cyclotron antenna coupling.

Nonadiabatic Interaction of Low-Energy Particles with Large-Amplitude Electron-Cyclotron Waves*

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The motion of electrons in a fundamental ordinary-mode electron cyclotron wave propagating perpendicularly to a magnetic field and of finite extent along the field is considered. If the wave frequency is below the cyclotron frequency, then, for low-enough energy particles, the electron motion is nonadiabatic for an extended period of time around the moment of trapping by the wave. This is in contrast to the situation previously analyzed where electron motion is assumed adiabatic except while crossing the separatrix. The nonadiabatic particles cross the separatrix at a time near to that at which a stable and unstable fixed point coalesce. The motion is analyzed by expanding the particle Hamiltonian about the time of coalescence and about the location of the merged fixed points, and by numerical solution of particle orbits of the expanded Hamiltonian. It is found that, in the limit that the initial action (energy) goes to zero, after passage through the r.f. beam, the particle has a probability of approximately 0.67 of having been accelerated by the wave to a final action approximately twice that associated with the low-amplitude resonance energy and 0.33 of returning to its initial energy. This contrasts with the adiabatic analysis which yields equal probabilites for the two final states.

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Gyrokinetic Simulations of Ion-Temperature-Gradient Modes with Sheared Poloidal Velocity*

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Data from DIII-D, TEXT, and other tokamak experiments indicate that the equilibrium poloidal velocity field can become strongly sheared accompanying the transition from L-mode to H-mode confinement and that the fluctuation levels are reduced.[1] Linear theory suggests that a sufficient amount of velocity shear can stabilize ion-temperature-gradient (ITG) modes when $L_s V_0'/c_s > O(1)$, where L_s is the magnetic shear length, V_0' is the radial derivative of the equilibrium $E \times B$ velocity, and c_s is the sound speed.[1] What effect does poloidal velocity shear have on ITG modes in the presence of finite-amplitude waves? To investigate both linear and nonlinear ITG physics issues, we have undertaken gyrokinetic particle simulations. We have extended 2D sheared slab, fully nonlinear gyrokinetic simulations of ITG modes to accommodate quiet-start initial conditions. Our fully nonlinear gyrokinetic simulations have shown that velocity shear reduces the level of ITG turbulence, but the simulations should be run longer and signal-to-noise should be improved. We are also undertaking 2D and 3D sheared slab, partially linearized (δf) gyrokinetic simulations to investigate velocity-shear effects on ITG modes with better signal-to-noise than in the fully nonlinear gyrokinetic simulations. We will compare our gyrokinetic simulation results to linear theory based on the use of a shooting code and to gyrofluid simulation results reported earlier by Waltz, et al. [2]

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ANALYTIC DERIVATION OF THE MAGNETOSONIC WAVE REFLECTION FIELD FOR ICRF HEATING IN TOKAMAK GEOMETRY*

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We consider ICRF heating of a minority ion species in tokamak geometry and analytically derive the transmission and reflection fields of incident *magnetosonic* radiation. We employ a model in which the minority guiding centers have magnetic moment $\mu = 0$, the curvature drift is negligible, and the guiding centers have radial velocity $\dot{r} = 0$. Then the toroidal guiding center velocity $v_{\|}$ is an invariant of the unperturbed dynamics. We consider a ray-phase-space $(\mathbf{x}, \mathbf{k})$ viewpoint in which wave action is transferred from each incident magnetosonic ray to a continuum of *minority-gyroresonant-ballistic* rays indexed by $v_{\|}$. These ballistic waves are eigenfunctions of the dispersion operator $D(\mathbf{x}, \mathbf{k}; v_{\|}) = \omega - \Omega(\mathbf{x}) - n\dot{\phi}(\mathbf{x}; v_{\|}) - k_\theta \dot{\theta}(\mathbf{x}; v_{\|})$, where $\mathbf{x} = (x, z)$, $\mathbf{k} = (k_x, k_z)$ are the poloidal guiding center position and wavevector, $(\dot{\phi}, \dot{\theta})$ are the toroidal and poloidal guiding center velocities, and (n, k_θ) are the toroidal and poloidal wavevectors. With the minority gyrofrequency of the form $\Omega(\mathbf{x}) = \Omega_o R_o/(R_o + x)$, the minority ballistic rays propagate in the k_x - direction. Each ballistic ray emits a reflected magnetosonic ray upon crossing the magnetosonic dispersion surface defined by $0 = D_A(\mathbf{x}, \mathbf{k}) = (k_o^2 - k^2)/4\pi(1 + \gamma^2)$, where $\gamma \equiv \omega/\Omega_M$, with ω the wave frequency, Ω_M the majority ion gyrofrequency, $k_o = \omega/c_A$, and c_A the Alfven speed. In this model z is an ignorable coordinate with k_z the corresponding dynamical invariant. The entire ray propagation and wave action transfer process can be viewed as occurring in a three dimensional ray phase space with coordinates $(x, z; k_x)$. We first derive the reflection field due to a single incident magnetosonic ray in a manner similar to previous work on the one dimensional slab model[1]. Then, since the wave equations are linear, we sum the reflected fields due to each of the incident rays and thereby obtain the full magnetosonic wave reflection field.

1. Huanchun Ye, *Wave Dynamics in Phase Space and Ion Gyroresonant Absorption*, Ph.D. thesis, University of California at Berkeley, 1989 (UMI No. 9103934).

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RF Active Confinement Control of Edge Turbulence: High Frequency Waves and Helicity Injection*

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The theories of high frequency RF active confinement control using Ion Bernstein waves (IBW) and Kinetic shear Alfven Wave (KSAW) helicity injection are presented. Motivation is derived from previous work [1] on shear suppression of edge turbulence by externally driven low frequency RF, where a mainly toroidally propagating incoming wave mode converts (at an edge placed Alfven resonance) to the radially propagating KSAW.

In the case of high frequency (near the ion plasma frequency) electrostatic waves, mean flow generation in a cylinder results from both a ponderomotive-like Reynold's stress and direct ion momentum input (similar to direct electron input in current drive.) A general discussion of momentum conservation is made with the key point that one can have negligible net momentum input with significant flow shear. Through Poisson's equation, this direct ion input can be broken into a direct electron input piece and a charge separation induced stress. For IBW applications, the mode conversion surface [2] (from a mainly toroidally propagating electron plasma wave to a mainly radially propagating Ion Bernstein wave) is placed at the edge. The main contribution to flow generation is from the Reynold's stress, which can be simplified by the cold plasma dispersion relation. The shear layer width is controlled by electron dissipation. A consequence of the dominant Reynold's stress is that quasilinear IBW flow drive only can generate an *inward* radial electric field, thus preventing a positive potential to control particle influx. This radial electric field shear is a possible cause for the already observed confinement improvement in PLT [3] and other machines using IBW heating. Estimates of power requirements for shear suppression over a few cm indicate about 100 kw of absorbed power is needed. Also included is a discussion of the severe limitations of quasilinear theory in light of recent progress [4] on strong parametric effects predicted for IBW heating. Finally, high frequency electrostatic wave mean flow generation is generalized to electromagnetic waves, such as ICRF.

A theory for KSAW helicity injection is also presented. Physics and the application to simultaneous flow and current drive are emphasized. It is found that wave helicity is *only* transported through boundaries (plasma boundary and Alfven resonance) and requires electron dissipation and ion inertia. KSAW direct electron momentum input and helicity injection current drive can be tailored to add constructively. The efficiency of the KSAW helicity injection current drive is smaller than resistive MHD helicity injection current drive and has favorable magnetic field scaling and unfavorable density scaling.

[1] G. G. Craddock and P. H. Diamond, *Phys. Rev. Lett.* **67**, 1535 (1991).
[2] M. Ono, et. al., *Phys. Fluids* **26**, 298 (1983).
[3] M. Ono, et. al., *Phys. Rev. Lett.* **60**, 294 (1988).
[4] M. Porkolab,et. al.,1990 APS-DPP Meeting.

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Collisionless Heating in the FRC from a Chaotic Conductivity

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Recent FRC experiments report an anomaly over the Spitzer heating rate $j_\theta E_\theta = j_\theta^2/\sigma$ and require that about 50% of the heating be put into the ions.[1] We suggest that there is a direct, irreversible heating of the ions due to the nonlinear dynamics near the reversal layer and provide an analytic form of the chaotic conductivity for this collisionless ion heating. In a reactor-size FRC the collisionless chaotic ion heating should completely dominate the collisional heating.

In the central region of long FRC the $E_\theta(t)$ field produces $E_\theta \times B_z(r)$ drift of the particles to the reversal layer ($x = r - r_s \to 0$) where the drift approximation breaks and the finite-Larmour-radius stochasticity drives the ions to qualitatively new orbits with the maximum kinetic energies of order $m_i L^2 \Omega^2$ where L is the thickness of the current sheet and $\Omega = eB_{\max}/m_i c$ is the cyclotron frequency at the edge of the current sheet. The tools of whisker map and the separatrix crossing theory are used to investigate the fraction of ions that are heated to this energy and the heating rate is expressed through the chaoic conductivity.

This work was supported by the US Department of Energy.

[1] M. Tuszewski, Nuclear Fusion **28**, 2033 (1988).

NUMERICAL THREE DIMENSIONAL EQUILIBRIA WITH PRESSURE ANISOTROPY*

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An energy functional given by $W = \int\int\int d^3x[B^2/(2\mu_0) + p_{\|}/(\Gamma - 1)]$ is proposed as a variational principle to determine three-dimensional ($3D$) magnetohydrodynamic (MHD) equilibria with anisotropic plasma pressure. It is demonstrated that the minimisation of W using an inverse coordinate spectral method reproduces the force balance relations that govern the MHD equilibrium properties of $3D$ plasmas with $p_{\|} \neq p_{\perp}$. This formulation of the anisotropic pressure equilibrium problem has been implemented in the preconditioned $3D$ VMEC code [1]. We have computed equilibria with highly localised anisotropic pressure distributions in a $3D$ ATF torsatron configuration. These pressure distributions would constitute appropriate models of a trapped energetic particle layer generated with perpendicular neutral beam injection or with radio frequency heating.

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SYMBOLIC SIGNAL PROCESSING AND PATTERN RECOGNITION

by

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How can we recognize many complicated patterns which complex dynamic processes exhibit? In order to be able to do this one has to find an appropriate symbolic language which is capable of reading all these patterns. The required language has a property of maximizing topological and metric entropies.

We have been developing algorithms for computer optimization of such symbolic languages. The preliminary results of these studies will be presented.

Poloidal Beta Scaling for a Bootstrapped Tokamak

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The idea of a steady-state bootstrapped tokamak has attracted considerable attention recently, thanks to the observations of significant bootstrap currents in most of the existing large tokamaks. We present a new scaling of the poloidal plasma beta, β_p, with the bootstrap fraction, f_b, for a steady-state plasma in the banana regime. This scaling, which assumes only that $n(r)/n(0) = [T(r)/T(0)]^\lambda$ but does not make any other assumption on the form of the density and temperature profiles, is of the form

$$\sqrt{\varepsilon}\ \beta_p = A(\lambda, Z_i)\ [a_1 f_b - a_2 f_b^2] \quad (1)$$

where ε is the aspect ratio, Z_i is the ionic charge, and a_1 and a_2 are numerical coefficients of order unity which, for large bootstrap fractions, depend weakly on the shape of the (normalized) seed and bootstrap current profiles. This new scaling, which is derived analytically from the steady-state neoclassical equations, differs from standard scalings [*Cordey et al., 1988; Devoto et al.. 1989; Kikuchi et al., 1990; Wilson, 1991; Pomphrey, 1991*] which exhibit a linear dependence of β_p on f_b. The standard scalings are derived by imposing specific forms of the density and temperature profiles, but more importantly, by imposing the profile of the total current $I(r) = I_s(r) + I_b(r)$ where I_s and I_b are, respectively, the seed and bootstrap profiles.This procedure, however, allows no control of the seed current profile, and has the unattractive feature that the seed current can change sign over a significant part of the plasma radius which may be difficult to realize in practice. We specify, instead, the seed current profile and make no assumptions on the total current profile.

For a given bootstrap profile, we show that β_p is maximized for a positive seed current localized near the axis. At $f_b = 1$, the term in the square brackets in Eq. (1) lies in the range 0.55 - 0.75 for a large class of current profiles. The function $A(\lambda, Z_i)$ is a monotonically decreasing function of λ. This is consistent with qualitative trends in TFTR data, in which higher β_p is obtained with flatter density profiles than in "supershots" with $\lambda \approx 2$.

It has been suggested by Boozer and co-workers [*Boozer, 1986; Weening and Boozer, 1992*] that a completely bootstrapped tokamak which requires no seed current is possible due to the "dynamo effect" caused by tearing modes [*Boozer, 1986; Bhattacharjee and Hameiri, 1986; Strauss, 1986*]. The tearing instabilities are expected to occur in the high-f_b regime due to the non-monotonicity of the q-profile and generate poloidal flux spontaneously near the axis, thereby dispensing with the need for an external seed. The validity of this scenario relies on sustaining strong pressure gradients near the axis despite the occurence of current relaxation due to tearing modes. Furthermore, since the temperature profile in a tokamak is determined by transport, it is important to examine whether the strongly peaked pressure profiles on which the mechanism relies are compatible with a complete set of steady-state transport equations in the high-f_b regime. We have carried out a numerical 1-D study for a relevant class of anomalous transport models, and find that the feasibility of a completely bootstrapped tokamak is very sensitive to the details of anomalous transport.

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Asymptotic Enstrophy Spectrum of 2-D Turbulence with Velocity Shear*

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In the presence of velocity shear (dv_y/dx), the spectrum of a two dimensional turbulent system can become highly anisotropic. We have solved a reasonable inviscid model for 2-D turbulence to obtain the anisotropic enstrophy spectrum. In the short wavelength limit (k >> 1) it is given by

$$I(k,\varphi) = \frac{\text{const.}}{k^2}\, e^{-b\cos 2\varphi}\left[I_0(b) + 2b\sum_{n=1}^{\infty}\frac{I_n(b)}{n^2+b^2}\,(b\cos 2n\varphi - n\sin 2n\varphi)\right],$$

where $b = (dv_y/dx)/12$, normalized to the radial decorrelation time, and φ is the phase angle in k_x-k_y plane shifted by $\pi/4$. The spectrum $I(k,\varphi)$, which is isotropic for $b = 0$, tends to resemble a dumbbell with the central part getting thinner and longer along $\varphi = 0$ axis as b is increased.

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Parallelizing Algorithms For Non-Linear Gyrofluid Turbulence Computations [1]

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Predictive scaling studies of 3-D gyrofluid turbulence in tokamaks are important to characterizing and understanding core fluctuation levels in current and proposed experiments. The computing power required to do these studies varies with the grid size N^4, thus rather coarse grids have been typical of computations using conventional supercomputers.

Massively parallel computers are now becoming available which can relax these limits. As a result, important physics issues which could not be adequately addressed before are now closer at hand. How the character of η_i turbulence changes with ρ_s/a is an example of one such issue.

One fly in the ointment is that to realize these gains generally requires that algorithms used in serial and vector computers must be adapted or redesigned to optimally use a particular target architecture.

We have created data parallel algorithms for the gyrofluid tokamak turbulence simulation code TRB optimized for the CM2/5 Connection Machine architecture while maintaining a coordinated parallel development of the CRAY-2 version of TRB for testing, control, and case construction.

An extensive graphics post-processing system designed for interactive network graphics enabling computer supported collaborative work has also been created as an integral part of the TRB code system. This post-processing system allows anyone with an X-Window and Internet access to examine the results of large turbulence simulations interactively and project the resulting images live or communicate them via e-mail.

Details of the implementation and comparative performance of block structured matrix solvers and pseudospectral convolution evaluators will be presented along with examples of the versatility of the post-processing system.

[1] Work performed for the U.S. DoE by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

Exact Analytical Solution of the Toroidal Singular Mode Equations

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A subset of the complete fluid equations governing the inner region of singular modes in toroidal geometry[1] is solved exactly and analytically. The subset includes toroidal curvature as well as ion and electron diamagnetic and $\mathbf{E} \times \mathbf{B}$ drifts, but not viscosity or thermal conductivity. The Fourier-transformed equations are expressed as a second-order ODE with singular points at 0 and ∞. Exact solutions are found in terms of confluent hypergeometic functions. A dispersion relation $\Delta' = \Delta(Q)$ is derived from the matching condition between inner and outer solutions in configuration space, with Δ' the ratio of small to large asymptotic coefficients in the ideal outer region and $\Delta(Q)$ a complicated function of the scaled growth rate Q obtained from the inner region analysis.

The most interesting result is a new instability for $Q > 1$ which exists in the absence of curvature and drift effects. Unlike most previous treatments, the validity of this one is not restricted by the constant-Ψ approximation or its relatives to the regime $Q \ll 1$. Most previous analytical treatment have found that systems with $\Delta' > 0$ are unstable, while systems with $\Delta' < 0$ are stable, although some works have replaced 0 by a threshold value Δ_C.[2] With the restriction $Q \ll 1$ removed, $\Delta(Q)$ is found to contain a pole at or near $Q = 1$, which has profound and surprising significance for stability theory. This pole was found in previous analytical[3] and numerical[4] treatments, but its significance was not appreciated. In the presence of the pole, there are strong instabilities for $\Delta' < 0$, with $Q > 1$ and approaching ideal MHD growth rates as $\Delta' \to 0$ from below. Thus, while $\Delta' > 0$ remains unstable, $\Delta' < 0$ is *more* unstable. The new instabilities are essentially ideal modes extending over more than one singular interval. The key role of the singular layer is to form a connecting bridge between adjacent ideal intervals, allowing a larger class of nearly ideal unstable modes to fit into the enlarged box. Beyond this main effect, the influence of resistivity on the growth rate gets weak as $\Delta' \to 0$ from below.

The full dispersion relation, including curvature and drift effects, is complicated and difficult to analyze, containing ratios of Γ functions of complex arguments. A complete analysis is performed by studying the locations of its rich variety of poles and zeroes and by means of Nyquist plots constructed with the help of Mathematica.[5] This analysis permits a deeper understanding of the number of unstable roots and of the relationship among various drift and resistive roots in different regimes of approximation than in previous treatments of drift tearing modes.

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TRANSPORT PROCESSES IN THE REVERSED-FIELD PINCH

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Over the past several years the theory of the RFP dynamo has become mature. Numerical simulations of nonlinear resistive MHD activity with zero plasma pressure have shown that the attainment and sustainment of reversed toroidal magnetic field results from the nonlinear interaction of a few long wavelength global MHD modes. More recently, resistive MHD simulations with finite plasma pressure have yielded repeated sawtooth oscillations during the sustainment phase that are similar to those observed experimentally. The plasma temperature, poloidal beta, and energy confinement time that result from these calculations are also consistent with experimentally measured values. The transport coefficients used in these calculations are classical; any anomalous transport must therefore result from the MHD fluctuations that produce the dynamo.

We now report on an analysis of the transport mechanisms that are active in these numerical simulations. Since the numerical model consists of resistive MHD with anisotropic thermal conduction, the only operative anomalous transport mechanisms are convection by global plasma flows and conduction in regions of stochastic magnetic fields. The effects of both transport mechanisms are calculated and compared. We find that the radial energy transport in these simulations of the RFP is dominated by parallel thermal conduction along stochastic magnetic field lines.

We also assess the role played by pressure driven modes in the RFP dynamo by artificially removing the pressure drive from the MHD modes during a sawtooth cycle. While slight quantitative differences occur, the sawtooth and relaxation events are relatively unchanged. We conclude that the primary relaxation mechanism remains current driven MHD modes. Preliminary results of a more detailed comparison between the nonlinear processes occurring in zero beta and finite beta relaxation will also be given.

Nonlinear Evolution of Resistive Tearing Mode Instability with Shear Flow and Viscosity*

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The nonlinear evolution of the tearing mode instability with equilibrium shear flow is investigated via numerical solutions of the resistive magnetohydrodynamic equations. The two-dimensional simulations are in slab geometry, are periodic in the x-direction, and are initiated with solutions of the linearized MHD equations[1]. The magnetic Reynolds number S is varied from 10^2 to 10^5, a parameter V that measures the strength of the flow in units of the average Alfvén speed is varied, and the viscosity as measured by the Reynolds number S_v satisfies $S_v > 10^3$. When the shear flow is small $V < 0.3$ the tearing mode saturates within one resistive time, while for larger flows the nonlinear saturation develops on a longer time scale. The two-dimensional spatial structure of both the flux function and the stream function distort in the direction of the equilibrium flow. The magnetic energy release decreases and the saturation time increases with V, for both small and large resistivity. The validity of the numerical solutions is tested by verifying that the total energy and the magnetic helicity are conserved. Total energy dissipation rate dE/dt decreases as the tearing mode approached its saturated state.

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Gyrokinetic Simulations of Unstable Toroidal η_i Modes*

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In sheared-slab geometry, η_i modes localized on neighboring mode rational surfaces are decoupled from each other in the linear phase. In toroidal geometry, overlapping modes are coupled to produce linear eigenmodes with radial coherence lengths much longer than the individual mode widths. Gyrokinetic simulations of toroidal η_i modes in the experimental regime of parameter space have observed the growth of such coherent eigenmodes. The growth of secondary instabilities destroys the radial coherence resulting in the formation of interacting *vortices* with scale lengths characteristic of the component individual *localized* modes. The ion thermal diffusivity reaches a large maximum value near saturation but thereafter decreases dramatically with the loss of radial coherence. The simulation results indicate that when stationarity is approached, the ion thermal diffusivity settles down to values exceeding those previously observed in sheared-slab simulations.

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RESONANT DAMPING OF TOROIDAL ALFVEN EIGENMODES IN GENERAL EQUILIBRIA

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We present a comprehensive analysis on the linear damping of the Toroidal Alfvén Eigenmodes, due to finite resonant coupling with the shear Alfvén continuous spectrum. Specifically, we demonstrate that the theoretical approach of "Generalized Ballooning Transform", previously employed to analyze the case of a zero-pressure tokamak with circular magnetic surfaces, can be extended, in the large aspect ratio limit, to general plasma equilibria. This approach, furthermore, can be cast into a form that allows a substantial analytical simplification in the numerical solution of the problem. Analytical and numerical results are given for arbitrary magnetic shear and finite pressure. The general scheme for the numerical implementation of this approach will also be discussed.

NONLINEAR POLOIDAL DENSITY VARIATION IN H-MODE PLASMAS*

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Poloidal plasma rotation speed in pre-H-mode and H-mode like plasmas can be large so that its Mach number $M_p = V_E B/v_{ti} B_p$ is of the order of unity. Here, V_E is the poloidal $\vec{E} \times \vec{B}$ speed, v_{ti} is the ion thermal speed, B_p is the poloidal magnetic field strength, and B is the magnetic field strength. Under that situation, the poloidal density variation is approximately governed by a nonlinear Ricatti type equation

$$\frac{2}{3} D \frac{d\chi}{d\eta} + (1 - M_p^2)\chi + 2A'(\chi^2 - \langle\chi^2\rangle) = 2\epsilon G \cos\eta \,, \tag{1}$$

where D represents the dissipation in the system, $A' \simeq M_p^2$, $G = (4M_p^4 + D^2)^{1/2}$, ϵ is the inverse aspect ratio, η is related to poloidal angle θ by the transformation $\eta = \theta - \zeta$, and $\zeta = \tan^{-1}(D/2M_p^2)$. The independent variable χ represents the density variation through the definition $N = \bar{N} exp(\chi)$ with N the plasma density and $\bar{N}$ a convenient normalization constant. When the dissipation is weak, Eq. (1) admits a shock-like solution. [R. D. Hazeltine, E. P. Lee, and M. N. Rosenbluth, Phys. Fluids **14**, 361 (1971); N. K. Winsor, J. L. Johnson, and J. M. Dawson, J. Comput. Phys. **6**, 430 (1970); J. M. Greene, J. L. Johnson, K. E. Weimer, and N. K. Winsor, Phys. Fluids **14**, 1258 (1971); J. M. Greene and N. K. Winsor, Phys. Fluids **16**, 863 (1973); K. C. Shaing, R. D. Hazeltine, and H. Sanuki, Phys. Fluids B **4**, 404 (1992)] Here, we solve Eq. (1) numerically for realistic plasma parameters. We find the density variation is up-down asymmetric, as first observed in CCT [R. J. Taylor, private communication, 1992]. The amplitude of the variation is of the order of $\sqrt{\epsilon}$. The variation of the parallel plasma flow speed is also large for being proportional to $1/N$. However, up-down asymmetry should be reduced when $M_p \gg 1$ and only in-out asymmetry persists.

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NONLINEAR ISLAND DYNAMICS

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A set of nonlinear equations is derived that describes the dynamics of magnetic islands in regimes where the plasma collisionality is low. Current singularities are avoided by taking electron inertia into account. In the absence of resistivity, the generalized flux function $\psi_e = \psi + (m_e c/e)v_h$ is conserved for single helicity modes. Here, ψ is the helical magnetic flux and v_h is the helical component of the electron fluid velocity. In regimes where the mode amplitudes exhibit spatial variations on a scale which is small compared to the gyroradius of a thermal ion, the electric potential and the current density are obtained as functions of space and the flux function ψ_e. In the case of small-scale magnetic islands, the effect of electron inertia is quite different for islands propagating with a frequency larger or smaller than the diamagnetic frequencies. For a larger frequency, the ψ_e-islands differ from those of ψ on the scale of the electron inertia skin depth, thereby shielding the X-points of ψ-islands. The current density peaks at the separatrix of a ψ_e-island but remains finite due to electron inertia. For small frequencies, ψ_e-islands do not exist.
On a spatial scale which is large compared to the ion gyroradius, the electric potential (i.e. the plasma displacement) still has the same functional dependence on space and ψ. This potential can be connected to the small-scale expression in a way which is analogous to the one employed in the linear treatment of resistive modes in the Fourier representation [1]. On this scale the current density is given by the drift-modified MHD momentum balance. The solutions have to be matched to the boundary conditions set by the ideal MHD solutions in the outer region.

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1992 SHERWOOD INTERNATIONAL FUSION THEORY CONFERENCE

A New Mechanism Of Thermonuclear Reaction

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The general formulae of fusion cross-section were first derived from quantum mechanics under the action of microscopic external fields of surrounding charged particles in a plasma.[1,2] These formulae show that there is a new quantum effect in nuclear fusion,i.e.the microscopic external fields have an effect on the fusion processes due to the potential reflection. When the external fields tend to zero or reacting nuclei are at high kinetic energy,these formulae can be simplified to Gamow formula. Averaging the product of fusion cross-section σ and relative velocity v over Maxwell-Boltzmann distribution,the fusion reaction rate $\langle \sigma v \rangle$ has been obtained. From which the thermonuclear reaction power density, energy-generation rate,etc.,can be given. They form a new mechanism of thermonuclear reaction. It shows that a certain amount of thermonuclear reaction can take place in dense,low temperature ($T < 1\times10^5$ K) plasmas. At superhigh temperature or low density,it is in agreement with the old thermonuclear reaction mechanism first presented by Gamow and Bethe. In dense,low temperature plasmas,its fusion reaction rate $\langle \sigma v \rangle$ is about tens orders of magnitude higher than that of the old mechanism. It is shown in principle that the old mechanism can be only applied to superhigh temperature or low density plasmas and is only a special example of the new mechanism. The new mechanism of thermonuclear reaction can be used not only to explain some mysteries and puzzles in astrophysics,such as the energy source in the giant planets and the Earth[1],the solar neutrino problem[3],a number of anomalous phenomena in elemental abundances in the Galaxy and the Universe, the cause and energy source for solar flare production, the luminosity variation phenomena in variable stars, etc., but also to interpret a number of abnormal fusion phenomena in dense,low temperature plasmas in laboratories.

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SHERWOOD THEORY MEETING 1992

Using LEX and YACC to Build a Parser for the MFEDB*

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The MFEDB[1] project accepts published experimental data from many sources. In order to make it easier for the various laboratories to contribute data, the MFEDB project has been willing to accept ASCII coded data in almost any format. Reformatting this data for insertion into the MFEDB has required writing a separate program to parse each type of file. Data from the DIII-D experiment which has been processed by the OneTwo code has turned out to be a rather difficult problem since the OneTwo code allows a variety of output formats.

For example, the output file from the OneTwo code consists of a header, several lines of comments, several NAMELISTs, diagnostic messages, a table label, a one line table, one or more time slices consisting of one or more tables with an optional label, column headings, and optional units, and data in tabular form. This can be followed by one or more summary sections consisting of a mixture of text and numerical data. There are five different table formats which allow a mixture of character, integer, fixed point, and floating point data.

We are developing a tool kit which accepts, as input, descriptions of the OneTwo formats and builds a parser. The parser can then operate on the OneTwo input files and directly enter the data into the database. This tool kit is being constructed using the tools LEX[2] and YACC[2] .

We will present and explain the LEX and YACC specifications for the OneTwo output datafiles and describe the embedded SQL[3] necessary to store the data.

* Supported by USDOE Grant DE-FG05-88ER53266

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Stability and Neoclassical Effects In High β Tokamaks

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In a recent paper[1] we have derived a general analytic solution for the equilibrium of a large aspect ration high β $(\beta \gg \varepsilon/q^2)$ tokamak. These equilibria are always stable to interchange and ballooning modes.[2] The kinetic stability is considered here. I will discuss particle orbits and general stability considerations. The analysis is simplified by the fact that the variation of $|\underset{\sim}{B}|$ over a surface is small. Note that the $|\underset{\sim}{B}|$ surfaces are always closed in these equilibria. Bootstrap current and other neoclassical effects are discussed.

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ONSAGER SYMMETRY OF TRANSPORT IN TOROIDAL PLASMAS

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Complete theories of transport contain thermodynamic cross terms, such as a particle flux driven by a temperature gradient. The matrix that relates the forces that drive the transport to the fluxes was shown by Onsager to be symmetric with the choices of the forces and fluxes rigidly constrained by thermodynamics. Unless the appropriate constraint is applied to the choice of forces and fluxes, the symmetry of the transport matrix is devoid of physical content since the forces and fluxes can always be defined to make the transport matrix symmetric. To obtain the constraint, the thermodynamic equation is written in the form $dS=\sum f_i d\alpha_i$ with the f_i intensive thermodynamic quantities and the α_i extensive. The forces that drive transport are the variations in the f_i and the α_i are the quantities being transported. The thermodynamic equation a toroidal plasma is

$$dU_t = T\,dS - p_t\,dV + \mu\,dN + I\,d\chi + G\,d\psi + \Phi_*\,dQ_c.$$

U_t is the total energy, electromagnetic plus plasma, T is the plasma temperature, S the entropy, p_t the plasma plus magnetic pressure, V the volume, $\mu=\mu_e+\mu_i/Z$ is the chemical potential, N the number of electrons, I the toroidal plasma current, $-\chi$ the poloidal magnetic flux, G the poloidal plasma current, ψ the toroidal magnetic flux, $\Phi_*=(\mu_i/Ze)+\Phi$ the electric potential corrected by the chemical potential of the ions, and $Q_c=eZ(N_i-N_e)$ the net charge. Defining the thermodynamic system as the region between two toroidal flux surfaces one finds that the thermodynamic forces are $\partial(1/T)/\partial\psi$, $-\partial(\mu/T)/\partial\psi$, $-\partial(I/T)/\partial\psi$, and $-\partial(\Phi_*/T)/\partial\psi$. The quantities being transported are the total energy, the number of electrons, the poloidal flux, and the charge. The fact that current is related to the force rather than the loop voltage, $(\partial\chi/\partial t)_\psi$, gives anomalies in the usual formulation of neoclassical theory. This work was supported by the US Department of Energy grant DE-FG058ER53176.

LYAPUNOV STABILITY OF TOROIDAL AXISYMMETRIC MHD EQUILIBRIA

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It has been found in previous work that the Grad-Shafranov equation can be obtained as the equilibrium condition of a variational principle, leaving as free functions the toroidal magnetic field and the pressure profiles [1]. The sufficient conditions obtained from Lyapunov analysis are weaker than those found by other authors [2], and the results obtained are a particular case of the stability analysis of the MHD plasma equilibria with axisymmetric toroidal flow. As a further exploration of case where no flow is considered, a numerical equilibrium code has been used to study the behavior of quantities which are relevant to the variational principle, such as the magnetic and thermal energies, magnetic helicity and entropy for a wide range of pressure profiles. The purpose of this work is to find some insight into the relaxation mechanisms of these systems, and a proper theoretical support to the profile consistency principle.

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A Three Dimensional, Toroidal Two Fluid Model with Hot Particles

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An electron fluid equation has been added to a 3D toroidal, resistive MHD code, MHD3D-GK[1], that also includes the effects of a population of hot ions, described by the gyrokinetic approximation. The MHD plasma velocity $\mathbf{V}$ in the Ohm's law, $\mathbf{E} + (1/c)\mathbf{V} \times \mathbf{B} = \eta \mathbf{J}_{th}$, has been changed to the electron fluid velocity $\mathbf{V}_e$, by the addition of the Hall term $(1/(cen_e))\mathbf{J}_{th} \times \mathbf{B}$ to the right hand side of the equation, along with the electron pressure gradient term $-\nabla p_e/(en_e)$, to produce the inertialess electron momentum balance equation. (Here $\mathbf{J}_{th}$ is the thermal (or fluid) component of the total plasma current.) The toroidal plasma equilibrium with drifts due to the new terms is investigated. Preliminary results are presented for the structure and evolution of the $m = 1$, $n = 1$ resistive kink mode. In this case, the introduction of the separate electron motion allows the reconnection layer to separate into two width scales, an outer one of the order of the ion gyroradius that describes the plasma motion and an inner one determined by the resistivity where the parallel current becomes large, in contrast to the one fluid MHD case where the plasma motion and the parallel current both vary on the smaller, resistive scale.

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Santa Fe, New Mexico, April 6-8, 1992

PHASE-SPACE FORMULATIONS FOR THE VLASOV-FLUID AND KINETIC-MHD MODELS†

LBL-31920A

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Kinetic-MHD models have recently played a major role in investigating the effects of energetic particles (e.g., alpha particles or neutral-beam ions) on the stability[1] of various macroscopic MHD modes. Recent developments in linearized Maxwell–Vlasov theory have identified the variational principles[2] for the linearized Maxwell–Vlasov equations, the Hermitian structure[3] for these linearized equations (given in terms of an indefinite inner product), and the expression for the quadratic free energy[4] used in investigating Maxwell–Vlasov equilibria. These developments were based on the use of a scalar field S, defined as the solution of $\partial_t S + \{S,\ H_0\} = e\ \psi_1$, where $\psi_1 = \phi_1 - \mathbf{A}_1 {\cdot} \mathbf{v}/c$ is the effective perturbed electromagnetic potential; the perturbed particle distribution function is $f_1 = \{S,\ f_0\} + (e\mathbf{A}_1/c)\ {\cdot}\{\mathbf{x},\ f_0\}$ and satisfies the linearized Vlasov equation. (Here, f_0 and H_0 are the unperturbed distribution and Hamiltonian, and f_0 satisfies the unperturbed Vlasov equation: $\partial_t f_0 + \{f_0,\ H_0\} = 0$, allowing for time-dependence in the unperturbed Maxwell–Vlasov system.) These developments will be briefly reviewed, and a discussion on the application of the low-frequency gyrokinetic formalism will be presented.

The purpose of the present work is to develop a phase-space formulation for the kinetic-MHD models, in which the MHD fluid displacement $\boldsymbol{\xi}$ is incorporated within the larger class of phase-space displacements generated by the scalar field S. The paradigm for such a phase-space formulation is the Vlasov-fluid model,[5] where the perturbed potential $\psi_1 = \boldsymbol{\xi}{\cdot}(\mathbf{E}_0 + \mathbf{v}{\times}\mathbf{B}_0/c)$ is used in the equation for the scalar field S. (The Vlasov-fluid model was recently used to obtain a stability criterion for energetic particle-Alfvén modes.[6]) Extensions of the Vlasov-fluid and kinetic-MHD models, in view of recent developments in linearized Maxwell–Vlasov theory, will be presented.

† *Work supported by U.S. Department of Energy under contract # DE-AC03-76SF00098.*

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APPLICATION OF THE PIES CODE TO CONFIGURATIONS WITH LARGE MAGNETIC ISLANDS

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The PIES code[1] determines MHD equilibrium configurations by direct integration along the field lines and does not assume the existence of good magnetic surfaces. Therefore it can be used for systems with magnetic islands and/or stochastic regions. In the case of good magnetic surfaces its predictions have been compared with known analytical solutions in some simple test cases, and with the predictions of another well known equilibrium code for more complex configurations.[2] In both cases the agreement was very good.

The work presented here is the beginning of a systematic study of the application of the PIES code to configurations with large magnetic islands. For this purpose we use the TJ-II flexible heliac,[3] which is very appropriate due to its versatility and small shear. This provides a very stringent test of the code because of the complicated shape of the TJ-II magnetic surfaces (the cross sections are strongly bean shaped and have a helical magnetic axis). We have mostly studied configurations for which $Nq = 3$ somewhere inside the plasma, and Nq close to 3 over the entire volume of the plasma (this is a consequence of the small magnetic shear). N is the number of periods ($N = 4$), and q is the winding number or reciprocal of the rotational transform. Typically, Nq changes from 3.02 at the magnetic axis to 2.92 at the plasma boundary. As should be expected, there is a large third order island.

First we study the zero pressure case, with no plasma currents. In this case the structure of the magnetic field can be obtained independently by following the field lines of the magnetic field created by the currents in the external coils. When this structure is compared with the predictions of the PIES code, the agreement is good if the number of modes carried in the code is adequate. The input given to the code is the shape of the plasma boundary (it must be a good magnetic surface). Afterwards we introduce some pressure. Because of the small shear, even a small pressure can have a large effect. Since the range of Nq in the plasma is so small, a small change in q can drive the resonance out of the plasma. The assumptions used for the islands are that both the pressure and the current density are constant inside them and continuous across the separatrices. The change in the magnetic structure with pressure is studied.

* Supported by the U. S. Department of Energy under Contract DE-AC02-76-CHO-3073 with Princeton University.

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ONSET OF THE SAWTOOTH CRASH*

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The evolution of the $m = 1$ island prior to the sawtooth crash is investigated. For relatively small island widths w, $w \sim 1/\Delta' << a$, the perturbed currents become comparable to the equilibrium currents and the "constant-psi" approximation becomes invalid. Here Δ' measures the free energy available for reconnection and a is the minor radius. A theory of thin island evolution is presented which generalizes the Rutherford theory[1] by taking into account the current nonlinearities. The resulting equations are found to be singular when the island becomes marginally stable in the ideal limit. This suggests that the sawtooth crash is triggered by a loss of stability within the island. However, the resulting estimate for the sawtooth period, $T \sim \tau_R/\Delta'^2$, where τ_R is the resistive diffusion time, is significantly shorter than experimental or numerical results. It is believed that this discrepancy can be resolved by the inclusion of curvature stabilization terms in the island evolution equation.

*This work was supported by a fellowship from the center for Theoretical Physics at the University of Maryland and by the Department of Energy.

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Quasilinear Diffusion of Photons In an ISI Beam.

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In the *wave-kinetic* theory of laser–plasma interactions developed by Tracy and Boozer,[1] the Hamiltonian nature of the ray equations can be exploited to great effect. We have applied Wigner function techniques Pioneered by McDonald, Kaufman,[2] and Boozer[3] to derive an appropriate wave–kinetic representation of the standard paraxial model of complex laser beams, such as those produced by *Induced Spatial Incoherence* (ISI) or other optical smoothing techniques.

Using quasilinear theory we have deduced an analytic expression for the diffusion tensor which governs the motions of photons in a background of sound wave turbulence, driven by an ISI type beam. Diffusion of rays may play an important role in the supression of filamentation. In the sub–threshold regime sufficiently fast ray diffusion could inhibit the formation of coherent structures, thus raising the threshold for filamentation.

We have developed a computer code that simulates the propagation of rays through a background of sound turbulence. Results of our simulations will be presented.

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ELECTROSTATIC HELICAL VORTICES

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Abstract

The electrostatic guiding-center plasma model, introduced twenty years ago by Taylor and McNamara, can be generalized to a situation in which the time-independent magnetic field lines are helical rather than straight. The parallel velocity of the charges is zero and the perpendicular velocity is given by the $\mathbf{E} \times \mathbf{B}$ drift. The "particles" are helical charged filaments that obey a Hamiltonian dynamics. Their phase spaces are finite inside a right circular cylinder with periodically identified ends. As such, they can exhibit a negative temperature phenomenon, and "vortex coalescence" is to be expected at high energies. A "sinh-Poisson" equation [1] for the helical states can be derived. The results include the possibility of helical vortex structures in tokamaks that are *not* accompanied by helical distortions of the current channel and magnetic field. In a cross-section of constant axial coordinate, the projected flow pattern can be convection cells of large spatial scale that could be effective agents for transporting both particles and heat. As in the case of the original electrostatic guiding-center plasma model, the dynamics can be generalized by adding higher-order drifts into the particle velocities. But also as in the original guiding-center plasma model, the most interesting and durable effects probably do not require these embellishments.

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Advanced Tokamaks in the Second Stability Regime*

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The second stability regime at high-q_0 provides a very attractive possibility for tokamak improvement. It is the only approach that allows a virtual 100% bootstrap current with equilibrium compatible profile. Equilibria in this regime are inherently safe against disruptions and can reach nT values comparable to those of the conventional first stability regime with plasma currents two to three times smaller. They are predicted to be stable against short wavelength resistive modes and there is some initial experimental evidence of an associated improvement in energy confinement. Access to the second stability regime requires some specific conditions on the tokamak geometry. A detailed investigation of this issue is presented with emphasis on the effects of aspect ratio, triangularity, and elongation.

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THE ISOTOPIC EFFECT AND IMPURITY DRIFT MODES*

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The first explanation[1] for the so-called isotopic effect, corresponding to the improvement in the energy confinement time that has been observed in deuterium plasmas when compared to plasmas with similar parameters, has been based on the properties of impurity driven modes excited at the edge of the plasma column. Thus the theory of impurity drift modes is examined in the fluid, collisional regime, appropriate for the edge region of toroidal experiments. The instability of the drift wave whose frequency is proportional to the impurity density gradient is examined in a plane geometry with a sheared magnetic field. These modes, where propogating in the electron diamagnetic velocity direction, are driven unstable by the temperature gradients of the main ions in regimes of relatively peaked impurity density: $\sigma = d\ell n n_Z / d\ell n n_i > 1$ and in the presence of dissipation (e.g., finite parallel ion thermal conductivity). The relevant conditions for instability are determined, as well as the cross-field structure of the eigenmodes. Another condition for instability that is relevant in regimes of weak temperature gradients and may be, therefore, less likely to occur, is that the impurity density gradient is opposite to the main ion density gradient.

Analytic techniques are used to identify the dependence[1] of this instability or the ion mass ratio, m_i/m_Z: the isotopic effect ($\tau \propto \sqrt{m_i/m_Z}$) is pointed out and the observation that confinement is no better in helium than hydrogen ($\tau \propto 1/Z_i$) is confirmed.

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

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Linear Stability Thresholds of Alpha Particle Driven High-n Toroidal Alfvén Eigenmodes*

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Several diverse physics mechanisms must be included to predict the instability threshold for the TAE mode in a burning plasma. We have used a large-aspect-ratio tokamak model to develop a consistent description of the growth and damping mechanisms of the TAE mode. This description includes: (1) A solution of the TAE spectrum under the assumption n >> 1 (but nr/R arbitrary)[1] that accounts for damping from the Alfvén continuum resonance; (2) An appropriate description of the alpha particle drive that accounts for an orbit excursion width from a flux surface that can be arbitrary compared to the scale size of the mode structure[2]; (3) Ion Landau damping that arises from the ion curvature drift response; (4) The response from electrons[3] to: (a) the small $E_{||}$ of the TAE mode, including the dissipative effect from the collisions of predominantly low-energy trapped electrons; (b) the dissipative interaction of the electron magnetic curvature drift with the TAE mode.

Detailed results will be presented that use a slowing-down alpha particle distribution generated from a thermonuclear source.

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Non-Ideal Analysis of Toroidal Alfvén Eigenmodes*

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Our previous studies[1,2] of the Toroidal Alfvén Eigenmode (TAE) demonstrated how the global eigenvalue (including continuum damping) can be evaluated, for essentially arbitrary toroidal mode number n, by determining the jump conditions near the resonant TAE surfaces where the parallel wave numbers for the m and m+1 poloidal harmonics satisfy $k_{\parallel m,n} = - k_{\parallel m+1,n}$. In ideal MHD theory, a Landau-type causality argument was used to determine how to treat the Alfvén resonances that arise even in the presence of toroidal coupling.

The matching procedure has now been generalized so that the appropriate jump conditions can be evaluated when non-ideal effects, including non-zero parallel electric field and finite Larmor radius, are accounted for. We find that when a certain parameter, ε, determined for example by finite resistivity or Larmor radius effects, can be treated as being small, the ideal theory defines where the branch cut in the complex frequency plane should be placed. Along the real frequency axis, the placement of the cut is always consistent with the causality argument as $\varepsilon \to 0$. However, for finite ε, the cut resolves into closely spaced poles. For a low collisionality system, these poles are intimately associated with kinetic Alfvén waves and, for practical parameters, may alter the Landau response even on the real axis.

Explicit examples will be presented.

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Alfvén Continuum Damping of Global MHD Modes

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Global MHD modes with a real positive ω^2 can exist only when the frequency falls within the Alfvén continuum gap (the global TAE modes). However, modes that interact weakly with the Alfven continuum can still be excited when the (alpha particle) excitation mechanism is strong enough to overcome the damping mechanisms. In this abstract, we present a method to calculate the contribution [1] of the Alfvén continuum to the damping of the global MHD modes. It relies on the fact that at the Alfven resonance, the real amplitude of the mode is logarithmically singular, the imaginary component jumps by π, with a possible additional jump in the real amplitude of the eigenfunction [2]. The frequency and growth rate of the mode is determined from the condition that the jumps in these amplitudes vanish. Thus, the method of solution is similar to that used in finding the stability criterion of tearing modes. The method is tested on an analytically solvable case with known singularity structures. It is then applied to the model TAE problem given in Ref. 1.

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Dynamics of Fluid Models for Collisional and Collisionless Drift-Wave Turbulence[1]

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We study fluid-based models for drift-wave turbulence with emphasis on the validity of quasilinear and mixing-length estimates of transport, spectral transfer, and the formation of coherent structures. Model equations studied include the Hasegawa and Wakatani equations for collisional drift-waves and a new fluid-based model for the collisionless trapped-electron mode (CTEM). The latter equations evolve the electrostatic potential $\hat{\phi}$ and the trapped-electron density $\hat{n}$ in a two-dimensional slab geometry. This model allows us to examine the competing effects of three different nonlinear interactions: the ion polarization drift nonlinearity, the ion $\boldsymbol{E} \times \boldsymbol{B}$ nonlinearity, and an electron $\boldsymbol{E} \times \boldsymbol{B}$ nonlinearity. We discuss linear dynamics, asymptotic estimates and implementation of simple closure for the CTEM model. One result is a competition of non-local electron Compton scattering and local mode coupling transfers to small scale with the familier ion-mediated transfer to large scale. Both models studied are amenable to solution with our two-dimensional pseudo-spectral code. We discuss preliminary numerical implementation of the CTEM model and extensive numerical studies of the dissipative drift-wave model. Simulation data for the dissipative model is compared with various turbulent transport estimates derived from mixing length and quasilinear theories. In the regime with long-lived coherent structures, the turbulent particle transport is less than standard quasilinear theories predict, leading to the speculation that structures impede transport.

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[1] Performed by LLNL for USDoE under Contr. W-7405-ENG-48.
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Efficient Higher-Order Symplectic Integration Algorithms

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ABSTRACT

Higher-order (≥ 4) symplectic integration algorithms combine the advantages of accuracy and long-time stability. We have previously developed efficient computational implementations of these algorithms through use of the Broyden update method for solving nonlinear equations. However, these methods suffered from the need to evaluate the force derivative matrix. Forest has recently shown that a fourth-order integrator can be composed of three second-order integrators of time steps of different sizes. As the implementation of the second-order symplectic integrator does not require evaluation of the force derivative matrix, we now have fourth-order integrators that need only the force functions, not their derivatives. We have implemented such an integrator in C. Examples of integrations of alphas in rippled tokamak geometries will be presented.

ICRF-DRIVEN CONVECTION IN TOKAMAKS*

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There is abundant experimental evidence showing that high-power ICRF heating can interact strongly with the edge plasma. Flattening of density and temperature profiles, generation of edge electric fields and associated E x B convection, and impurity generation are sometimes observed to be related to ICRF heating. On large tokamaks such as JET and TFTR, these effects are observed to disappear when the antenna phasing is properly chosen to cancel the rf magnetic flux linking field lines which intersect the antenna structure and nearby limiters. This suggests that rf sheaths are the underlying cause of the antenna-edge interaction. This connection has been firmly established with regard to metal impurity release on JET, and a sheath-theory based prescription has been obtained to virtually eliminate such impurities.[1] It is also observed on JET that the threshold power for H-mode formation is higher and the energy confinement time lower in monopole than in dipole phasing, in agreement with the condition for large rf sheath voltages. In the present work, we attempt to understand this phasing dependence in terms of rf sheath-driven convective cells.

The basic idea[2] is that the "rectification" of the oscillating rf fields by the antenna sheaths produces a net time-averaged and spatially-varying potential $\Phi_o(x,y)$ which is of the form to drive convective flow in the SOL. We use a modified convective cell equation[2] for the SOL plasma which explicitly takes into account the finite length of the field lines and the appropriate sheath boundary condition for $J_{||}$ at the limiters with the antenna sheath potential Φ_o entering as a boundary condition. The time-dependent 2D equations for the driven system are solved by a 3rd order accurate "upwind differencing" algorithm for the vorticity and a modified tridiagonal solve for the field-line averaged potential. The simulation confirms that the rf convective cells can strongly modify the poloidal velocity shear in the SOL and are good candidates to explain the observed interaction with ICRF H-modes. The limitations of the present simulation with regard to the question of edge turbulence will also be discussed.

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Toroidal Effects on Drift Wave Turbulence*

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Drift instabilities driven by density and temperature gradients in a toroidal plasma are investigated in both linear and nonlinear regimes by particle simulation. We employ the Toroidal Particle Code (TPC) in a variety of configurations. Emphasis is placed on comparison of fully toroidal simulations to their cylindrical couterparts.

The major physical effect of toroidicity is the coupling of linear eigenmodes of the drift waves. Compared with cylindrical systems the toroidally coupled eigenmodes extend widely (sometimes globally) in the minor radial direction, showing common eigenfrequencies across the radius. This coupling effect essentially annihilates ion Landau damping and leads to enhanced mode growth rates.

In the case of the universal mode ($\eta_e = \eta_i = 0$ where $\eta = \partial \ln T / \partial \ln n$ and e and i indicate electron and ion quantities respectively) the mode is destabilized by the toroidicity and results in much higher level of transport. As the temperature gradient is increased ($\eta_i, \eta_e > 0$), the instability growth rate becomes greater and ion diamagnetic effects more important; individual modes at the rational surfaces tend to localize.

The toroidal effects manifest themselves in that (i) the modes become toroidally coupled and globally extend in the radius, (ii) the growth rate becomes greater, (iii) the eigenfrequency becomes globally constant, (iv) the resultant temperature relaxation is global, (v) the heat conduction is enhanced over the cylindrical counterpart by an order of magnitude, and (vi) the temperature transport tends to be greater toward the outer minor radius. Many of these features are in agreement with theoretical expectations.

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APPROXIMATION TO MHD IN THE LOW RESISTIVITY LIMIT*

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The Grad-Hogan equations for quasi-equilibrium resistive evolution are solved in a nontrivial topology, a 2D simulation of the Doublet configuration, for a decreasing sequence of resistivities, η. The Doublet is modulated by a sinusoidal flux driver, so that the total flux in the figure-eight separatrix evolves toward a stationary oscillation. As $\eta \rightarrow 0$, the solutions show behavior typical of approach to a singular zero-resistivity limit. The time-dependent limit appears to be "adiabatic" only in a generalized sense insofar as jumps in the fluid variables may occur across the separatrix. As the resistivity drops a resistive sheath, or boundary layer, of decreasing thickness is formed about the separatrix. Outside the sheath, the plasma approaches the adiabatic state: most strikingly, the flux freezes hard and the current becomes nearly stationary, appropriately for a superconductor.

We show how to extrapolate the resistive information to formulate an appropriate generalized adiabatic evolution to approximate the low resistivity evolution. Both, the adiabatic and resistive equations are solved by Grad's alternating dimension method. The advantage of the adiabatic approximation is that the run time for AD code is short and the algorithm can be executed easily on a microcomputer. In contrast, the resistive algorithm converges slowly at low resistivity and, as the resistivity drops, the run time rapidly increases to durations infeasible even for a supercomputer. The approximating adiabatic solution may be adequate of itself or can be used to accelerate convergence of the resistive algorithm by providing an initialization not too far from the correct resistive solution.

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Gyrokinetic δf simulation in a toroidal metric*

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The δf algorithm for kinetic plasma simulation analytically separates the background distribution from the perturbed distribution while preserving all nonlinearities. In this scheme, the "particle" species is used to describe only the perturbed distribution, resulting in a tremendous decrease in noise over standard PIC methods, and is thus of great practical applicability to the problem of transport in confined plasmas.

The gyrokinetic and δf algorithms have been implemented in the Toroidal Particle Code (TPC), a multi-geometry, multi-algorithm, and multi-platform plasma simulation code. Several different models (including full kinetic, drift or gyrokinetic, with or without δf, and adiabatic) can be switched on or off in order to easily compare the results using different algorithms. This "all-in-one-code" approach offers a highly controlled setting for detailed comparisons between competing approaches, as well as providing a framework for development of new methods. Such an approach is increasingly relevant in the context of ambitious research efforts such as the proposed Numerical Tokamak.

The gyrokinetic equation utilized in this work is that of Dubin *et al*, applied to a general coordinate metric. The metric-dependent terms are retained without approximation in our treatment. The gyroaveraging of the ion density and interpolated electric field is accomplished by a variant of the usual four-point method. Terms scaling as $(k_\perp \rho_i)^2$ in the Poisson equation are expanded as $\rho_i^2 \nabla_\perp^2$. The Poisson equation is inverted via iterative application of a rapid elliptic solver, and convergence is found to be rapid in most cases.

The addition of a δf response makes the system considerably more complex, since all operations dealing with the particles must be cognizant of the separation into background and perturbed distributions, and is handled in a straightforward fashion in the framework of TPC. The time evolution of the system is governed by a combination of movement of markers (i.e. "particles") through phase space and the time evolution of each marker's value of the perturbed distribution δf_j. The latter is advanced in time via a predictor-corrector method.

In this work we discuss these issues and compare results for η_i driven instabilities in a number of different configurations, including a slab or toroidal metric, and either a full kinetic, gyrokinetic, or gyrokinetic δf ion response.

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Energy Confinement Scaling in the ATF Torsatron†. R. A. Dory, M. Murakami and the ATF Experimental Team, **ORNL**.—The energy confinement time from data in a multi-shot database, representing diverse discharge conditions, was compared previously with global scaling expressions [R. A. Dory, M. Murakami, W. R. Wing and the ATF Team, Comments on Plasma Physics and Controlled Fusion, **14**, 237 (1991)]. In order to broaden the scope of the scaling studies, new experiments have been performed in which individual plasma parameters are modulated during single discharges of 5-10 s total duration [M. Murakami and the ATF Team, European Physical Society Meeting, **19** (1992)]. The modulation results reinforce the earlier observation that the gyro-Bohm scaling is a closer fit than Bohm-like scaling. The new data also confirm dependence, found in the earlier work, of stored energy W_{dia} on dimensionless parameters as $\beta^{0.4\pm0.1}$ and $\nu^{*\,-0.18\pm0.04}$. Use of the dimensionless corrections from these experiments provides as good fit to the multi-shot data as did the regression, by mitigating correlations (collinearity) in control parameters, $\overline{n_e}$, P_{abs}, B_o. Of the theoretical models compared by Christiansen and colleagues [J. P. Christiansen, *et. al.*, Nuclear Fusion **30**, 1183 (1990)] with tokamak data, the one nearest the ATF result is the resistive MHD turbulence model. In ATF, as in tokamaks, there remains an adverse dependence of τ_E on auxiliary power, but the dependences on β and ν^* suggest that it will be partly offset because the increased heating power also leads to higher β and T_e (lower collisonality).

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Low-Frequency Fluctuations in Plasma Magnetic Fields*

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It is shown that even a non-magnetized plasma with temperature T sustains zero-frequency magnetic fluctuations in thermal equilibrium. Fluctuations in electric and magnetic fields, as well as in densities, are computed. Four cases are studied: a cold, gaseous, isotropic, non-magnetized plasma; a cold, gaseous plasma in a uniform magnetic field; a warm, gaseous plasma described by kinetic theory; and a degenerate electron plasma. For the simple gaseous plasma, the fluctuation strength of the magnetic field as a function of frequency and wavenumber is calculated with the aid of the fluctuation-dissipation theorem. This calculation is done for both collisional and collisionless plasmas. The magnetic field fluctuation spectrum of each plasma has a large zero-frequency peak. The peak is a Dirac-delta function in the collisionless plasma; it is broadened into a Lorentzian curve in the collisional plasma. The plasma causes a low frequency cutoff in the typical black-body radiation spectrum, and the energy under the discovered peak approximates the energy lost in this cutoff. When the imposed magnetic field is weak, the magnetic field wave vector fluctuation spectra of the two lowest modes are independent of the strength of the imposed field. Further, these modes contain finite energy even when the imposed field is zero. It is the energy of these modes which forms the non-magnetized zero-frequency peak of the isotropic plasma. In deriving these results, a simple relationship between the dispersion relation and the fluctuation power spectrum of electromagnetic waves is found. The warm plasma is shown, by kinetic theory to exhibit a zero-frequency peak in its magnetic field fluctuation spectrum as well. For the degenerate plasma, we find that electric field fluctuations and number density fluctuations vanish at zero frequency; however, the magnetic field power spectrum diverges at zero frequency.

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Magnetic Surfaces in a Steady-State Tokamak*

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We study a toroidal plasma in a tokamak with externally given toroidal and poloidal magnetic fields as well as self-consistently interacting internal currents[1]. The unperturbed magnetic surfaces are described by the well-known nonlinear "standard map". When the magnetic field is allowed to carry an internal current, the self-interaction of these currents disturbs the integrity of the magnetic surfaces. We carry out a computational study of the effects of the interacting internal current filaments, measuring the diffusion of field lines from the unperturbed surfaces, and find the self-interaction to be a significant effect which always serves to increase diffusion. Perfect surfaces are difficult to maintain even when magnetic islands do not overlap. Diffusion from the current interaction dominates when current fluctuations reach ~10% of the applied field.

[1]J.B. Taylor, IFSR 447 (1991).

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Investigation of Possibility of LH/FW Synergism

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Synergistic effect of current drive with the simultaneous application of directional lower hybrid power and symmetric monopole ICRF power was observed in JET. The addition of ICRF was found to greatly enhance the tail electron temperature produced by LH power. One possibility is that the ICRF power has low $n_{\parallel}$ components which directly interact with the asymmetric tail drawn out by LH power, and thus further enhance the tail. An estimate of the quasilinear diffusion coefficient of ICRF indicates that this effect is considerably weaker than what the experiment shows. An alternative possibility is that the ICRH alters the lower hybrid spectrum and the new tail is the result of the altered LH-spectrum. In this work we investigate this possibility. The scattering of the LH-power by the fluctuations of plasma due to ICRF is calculated using a cold plasma model. The change in lower hybrid spectrum is estimated and the implication on the electron tail temperature due to this changed LH-spectrum is estimated.

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A New Modeling of Anomalous Ion Thermal Transport by the Toroidal Ion Temperature Gradient Mode*

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Many recent experimental[1] and theoretical[2] studies of the anomalous ion thermal transport shows that it is difficult to explain the observed increase of the ion thermal conductivity χ_i with minor radius by the ion temperature gradient mode[3]. In this work, this radial profile problem of the χ_i is reconsidered using the more complete study of the toroidal η_i-mode. It is first found that the electromagnetic effect gives a stronger stabilization than shown in previous approximate studies, and may well explain the decrease of the χ_i in the core region. It is shown that this feature also agrees well with recent experimental results[1] in JET and DIII-D in the hot ion regime, where, for high β_i there are quite low (~ 0.3 m^2/s) ion thermal diffusivities in the core ($\leq a/3$). Now, with the electromagnetic effect, the theoretical χ_i calculated by the simple mixing length formula appears to be smaller than the experimental value over all minor radii, in particular, near the edge region. To resolve this problem, we propose a new mixing length formula of the χ_i, based on the inverse cascade phenomena. It is shown that the new formula gives the radial profile of the χ_i and the scaling law in the current and the toroidal magnetic field that tend to agree with the experiment.

[1]M.C. Zarnstorff et al. in Plasma Phys. and Contr. Nucl. Fus. Res., 1990, Proc. of the 12th Internatl. Conf., Washington (IAEA, Vienna, 1991), Vol. I, p. 109; A. Taroni et al. ibid, Vol. I, p. 93; K.H. Burrell et al. ibid, Vol. 1, p. 123.
[2]W. Horton et al., IFSR 501, to be published in Phys. Fluids (1992).
[3]B. Coppi and F. Pegoraro, Nucl. Fusion **17**, 963 (1977).

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