Saralyn Stewart

1991

INTERNATIONAL SHERWOOD FUSION CONFERENCE

APRIL 22-24, 1991
SEATTLE, WASHINGTON

Seattle, Washington

UNDER THE AUSPICES OF STI OPTRONICS, INC.

1991
INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

APRIL 22-24, 1991
STOUFFER-MADISON HOTEL
SEATTLE, WASHINGTON

Under the auspices of

STI OPTRONICS, INC.
Bellevue, Washington

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GENERAL INFORMATION

* 196 papers were submitted, of which 16 were selected for oral presentation.

* The Invited papers will be presented in the Federal-Superior room, Monday and Tuesday mornings beginning at 8:30 a.m.

* Oral papers will be presented in the Federal-Superior Room 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 "New Directions" will be held on Monday evening, April 22 from 8:00-10:00 p.m. in the Federal-Superior room.

* Poster sessions will be held in the Municipal/Foyer rooms Monday and Tuesday afternoons from 2:00-6:00 p.m. and Wednesday morning from 10:30 a.m-12:30 p.m.

* A Northwest Indian style salmon bake on Blake Island will be held on Tuesday evening from 6:15 -10 p.m. (Bus departure from hotel lobby entrance at 6:15 p.m.)

* A Companion's breakfast will be held on Monday morning at 9 a.m. in the State Dining Room (second floor).

* Refreshments will be served in the Ballroom foyer, consisting of coffee and tea, Monday through Wednesday mornings at 9:30 a.m. and beer and soft drinks Monday and Tuesday afternoons at 3:00 p.m.

* Requests for special meetings should be made with Bonnie Hertz at the Conference Registration Desk.

1991 International Sherwood Fusion Theory Conference
Stouffer Madison Hotel, Seattle, Washington
April 22-24, 1991

Schedule

Registration — Ballroom Foyer (lower level)

Sunday, April 21 — 6:00 - 10:00 p.m.
Monday, April 22 — 7:45 a.m. - 5:00 p.m.
Tuesday, April 23 — 7:45 a.m. - 5:00 p.m.
Wednesday, April 24 — 8:00 a.m. - 10:00 a.m.

Oral and Poster Sessions

Invited and Oral Papers — *Federal-Superior*
Posters — *Municipal/Foyer*

Monday

8:20 a.m.		Welcome	L. Steinhauer, Local Chairman	
8:30 - 9:20 a.m.	1 A	Invited Paper	V.E. Zakharov	
9:30 a.m. -12:30 p.m.	1 B	Oral Session		(6 — 25 min orals)
2:00 - 4:00 p.m.	1 C	Poster Session		(36 posters)
4:00 - 6:00 p.m.	1 D	Poster Session		(36 posters)
8:00 - 10:00 p.m.	1 E	Special Session on New Directions		

Tuesday

8:30 - 9:20 a.m.	2 A	Invited Paper	W. Gekelman	
9:30 a.m. - 12:30 p.m.	2B	Oral Session		(6 — 25 min orals)
2:00 - 4:00 p.m.	2 C	Poster Session		(36 posters)
4:00 - 6:00 p.m.	2D	Poster Session		(36 posters)

***Salmon Bake* — 6:15 - 10:00 p.m.**
(Bus departure from hotel lobby entrance at 6:15 p.m.)

Wednesday

8:30 - 10:30 a.m.	3B	Oral Session	(4 — 25 min orals)
10:30 - 12:30 a.m.	3 C	Poster Session	(36 posters)

Coffee and Tea — Monday through Wednesday — 9:30 a.m. - 12 noon
Beer and Soft Drinks — Monday and Tuesday — 3:00 - 5:30 p.m.

Monday Oral Schedule

8:20 a.m.		L. Steinhauer, Local Chairman, Opening Remarks
8:30 a.m.	1 A	Chair: F. Perkins
		V.E. Zakharov, *Spectra of Drift-Wave Turbulence*
Oral Papers	1 B	Chair: Y.H. Ichikawa
9:30-9:55 a.m.		Sidikman et al., *Fluctuations and radial electric fields*
10:00-10:25 a.m.		Scott, *Self-sustainment in collisional drift-wave turbulence*
10:30-10:55 a.m.		Guzdar et al., *3D nonlinear drift resistive ballooning modes*
11:00-11:25 a.m.		Kim, *Neoclassical poloidal and toroidal rotations*
11:30-11:55 a.m.		Isichenko, *Anomalous transport by percolation*
12:00-12:25 p.m.		Dominguez, *Atomic mass scaling in the drift wave model*
Poster Session		
2:00-4:00 p.m.		1 C
4:00-6:00 p.m.		1 D
Special Session on New Directions		
8:00-10:00 p.m.	1 E	Chair: A. Hasegawa
		J. Dawson, *Non-Energy Applications of Fusion Research*
		L. Shohet, *The Plasma Physics of Plasma Processing*

Tuesday Oral Schedule

8:30 a.m.	2 A	Chair: B. Cohen
		W. Gekelman, *Experiments on Collisionless Reconnection and the Interaction of Current Channels*
Oral Papers	2B	Chair: W. Tang
9:30-9:55 a.m.		Hedrick, *Landau fluid equations for Alfvén waves*
10:00-10:25 a.m.		Chang et al., *Unified plasma fluid/kinetic equations*
10:30-10:55 a.m.		Aydemir, *Studies of m=1 modes in high-temperature plasmas*
11:00-11:25 a.m.		Jensen et al., *Rotation velocity profile control*
11:30-11:55 a.m.		Kupfer et al., *Fast electron transport in current drive*
12:00-12:25 p.m.		Sigmar et al., *Losses of alpha particles*
Poster Session		
2:00-4:00 p.m.		2 C
4:00-6:00 p.m.		2 D

Wednesday Oral Schedule

Oral Papers	3B	Chair: D. Barnes
8:30-8:55 a.m.		Cheng, *Alpha particle destabilization of the TAE modes*
9:00-9:25 a.m.		Berk et al., *Structure of toroidal Alfvén eigenmodes*
9:30-9:55 a.m.		Greene et al., *A tearing mode energy principle*
10:00-10:25 a.m.		Coppi et al., *Collisionless magnetic reconnection*
Poster Session		
10:30-12:30 p.m.		3 C

1991 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

Stouffer Madison Hotel, Seattle, WA
April 22 - 24, 1991

REGISTRATION - Ballroom Foyer (lower level)
Sunday, April 21 - 6:00pm - 10:00pm
Monday, April 22 - 7:45am - 5:00pm
Tuesday, April 23 - 7:45am - 5:00pm
Wednesday, April 24 - 8:00am - 10:00am

MONDAY MORNING

WELCOME - 8:20am - L. Steinhauer, Local Chairman

1A Invited Paper
8:30am - 9:20am
Presiding: F.W. Perkins

1A1. Spectra of Drift-Wave Turbulence. V. E. Zakharov.

1B ORAL SESSION
9:30am - 12:30pm
Presiding: Y.H. Ichikawa

1B1. Relating Turbulent Fluctuations and Radial Electric Fields: A Drift Wave Turbulence Model. K. L. Sidikman, B. A. Carreras, N. A. Dominguez, L. Garcia, and P. H. Diamond.
1B2. The Mechanism of Self-Sustainment in Collisional Drift-Wave Turbulence. B. D. Scott.
1B3. 3D nonlinear Drift Resistive Ballooning Mode-Induced Transport and Poloidal Rotation. P. N. Guzdar, J. F. Drake, A. B. Hassam, D. McCarthy, and C. S. Liu.
1B4. Neoclassical Poloidal and Toroidal Rotations in Tokamak Plasmas. Y. B. Kim.
1B5. Anomalous Transport by Percolation. M. B. Isichenko.
1B6. Atomic Mass Scaling in the Drift Wave Model. R. R. Dominguez.

MONDAY AFTERNOON

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

1C1. Evidence of Stochastic Diffusion Across a Cross-Field Sheath due to Kelvin-Helmholtz Vortices. C. K. Birdsall, X. Q. Xu, S. E. Parker, and A. J. Lichtenberg.
1C2. Three-Dimensional Particle Simulation of Ion Temperature Gradient Mode on Massively Parallel Computers. Y. Matsuda, T. J. Williams, and J. Byers.

1C3. Pressure Driven Collapse of Magnetic Islands and H-Mode in Tokamaks. L. E. Zakharov, A. I. Smolyakov, and A. A. Subbotin.
1C4. ICRF Coupling at Low Edge Densities. S. C. Chu.
1C5. Ideal MHD Stability of High Poloidal Beta Equilibria in TFTR. S. A. Sabbagh, M. E. Mauel, G. A. Navratil, M. G. Bell, R. V. Budny, M. S. Chance, E. D. Fredrickson, S. C. Jardin, J. Manickam, D. C. McCune, K. M. McGuire, R. M. Wieland, M. C. Zarnstorff, M. W. Phillips, M. H. Hughes, and J. Kesner.
1C6. Reduction of Tokamak Ion Transport in the Banana Regime by Orbit Squeezing. K. C. Shaing and R. D. Hazeltine.
1C7. Studies of the Finite Amplitude Eta(i)-Mode. A. D. Beklemishev, W. Horton, and Y. H. Ichikawa.
1C8. Fluid/Kinetic Models for Alpha Particle Induced Instabilities. Y. L. Ho, D. C. Barnes, Z. Mikic, R. A. Nebel, D. D. Schnack, and K. T. Tsang.
1C9. Nonlinear Dynamics of the Relativistic Standard Map. Y. Nomura, Y. H. Ichikawa, and W. Horton.
1C10. Collisionless Reconnection and the Sawtooth Crash. J. F. Drake and R. G. Kleva.
1C11. A Universal Instability in Fluid Dynamics. A. Lifschitz and E. Hameiri.
1C12. Stabilization of TAE Instabilities via Ion Landau Damping. R. Betti and J. P. Freidberg.
1C13. Mode Conversion in Global Wave Calculations. P. E. Moroz and N. Hershkowitz.
1C14. Quasilinear Driven Transport in a Sheared Flow Field. K. S. Riedel.
1C15. Sheared Electric Field-Induced Suppression of Edge Turbulence Using Externally Driven R.F. Waves. G. G. Craddock and P. H. Diamond.
1C16. Finite Shift Effect on Ballooning Modes Stability in a Toroidally Rotating Plasma. S. Sen.
1C17. Comparison of the Performance of a Fluid Code on Different Machines. V. E. Lynch, B. A. Carreras, J. B. Drake, and J. N. Leboeuf.
1C18. Efficient Simulation of High-n Turbulence in Ballooning Coordinates. A. M. Dimits.
1C19. Stabilization of Drift Modes by Sheared Plasma Rotation. F. L. Waelbroeck, T. M. Antonsen, Jr., and A. B. Hassam.
1C20. Tokamak Transport Based on the Thirteen Moments Model. M. K. Tippett.
1C21. The Effect of Orbit Averaging on Plasma Turbulence and Turbulent Transport. H. E. Mynick and S. J. Zweben.
1C22. Weak Turbulence Theory of Langmuir Waves: A Reconsideration of Validity of Quasilinear Theory. Y.-M. Liang and P. H. Diamond.
1C23. Numerical Study of n=1 Stability of PBX-M at High q(0). J. J. Ramos.
1C24. Gyrokinetic Particle Simulation of ITG Modes in General Toroidal Geometry. D. Hua, T. K. Fowler, and X. Q. Xu.
1C25. Toroidal Microinstability Studies of Confinement Trends in TFTR. W. M. Tang and G. Rewoldt.
1C26. Alfven Continuum Gap and the High n Gap Mode in a Noncircular Tokamak. M. S. Chu, J. M. Greene, L. L. Lao, A. D. Turnbull, and M. S. Chance.
1C27. Ion Transport from Kinetic eta(i) Modes: Comparisons with Experiment and Fluid Results. M. Kotschenreuther.
1C28. Comparison of Local and Non-local Kinetic Theory of Ion Temperature Gradient Modes. J. Y. Kim and W. Horton.
1C29. Gyrokinetic Simulation of Energetic Particle Effects on Tokamak Stability. K. T. Tsang.
1C30. Renormalization Group Analysis of Two Dimensional MHD Turbulence. W.-L. Zhang and P. H. Diamond.
1C31. Perturbative Transport due to Drift Wave Fluctuations. A. A. Thoul, P. L. Similon, and R. N. Sudan.
1C32. Net Transport Equations for a Tokamak Plasma. J. B. Hollenberg and J. D. Callen.
1C33. Effect of Drifts on the Diffusion of Runaway Electrons in Tokamak Stochastic Magnetic Fields. J. R. Myra and P. J. Catto.
1C34. Coupled Energy and Current Transport. F. Pegoraro and B. Coppi.
1C35. Stabilization of Sawteeth in Tokamaks by Sheared Poloidal Flows. R. G. Kleva.
1C36. Examination of Sawtooth Stabilization by Localized Electron Cyclotron Heating Near the q=1 Surface. A. H. Kritz, J. Manickam, M. Yamada, and S. Tanaka.

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

1D1. Inertia Effects on the Rigid Displacement Approximation of Tokamak Plasma Vertical Motion. R. Carrera, R. R. Khayrutdinov, E. A. Azizov, J. Q. Dong, and E. Montalvo.
1D2. Gyrokinetic Modeling Including Collisions: Neoclassical Diffusion Studies. S. Ma, R. D. Sydora, and J. M. Dawson.
1D3. Nonlinear Evolution of Ion-Streaming Instabilities along Auroral Fields. J. H. Han, W. Horton, and J. N. Leboeuf.
1D4. The Structure of Ideal MHD Alfven Modes. A. D. Turnbull, M. S. Chance, M. S. Chu, L. L. Lao, J. M. Greene, and E. J. Strait.
1D5. Ellipticity Induced Alfven Eigenmodes. J. P. Freidberg and R. Betti.
1D6. ICRF Action Transfer from Magnetosonic to Ion Bernstein Wave. D. R. Cook, A. N. Kaufman, and E. R. Tracy.
1D7. Efficiency of RF-Driven Current in a Noncircular Tokamak. C. F. F. Karney.
1D8. Nonlinear Evolution of Resistive Tearing Mode Instability with Shear Flow and Viscosity. L. Ofman, P. J. Morrison, and R. S. Steinolfson.
1D9. Numerical Modeling of ICRF Heating and Current Drive. N. Hershkowitz, P. E. Moroz, R. Majeski, and J. A. Tataronis.
1D10. Energy-Confinement-Timescale Numerical Tokamaks. B. I. Cohen, R. H. Cohen, and W. M. Nevins.
1D11. ICRF-Driven Convective Cells in the Tokamak Edge Plasma. D. A. D'Ippolito, J. R. Myra, J. Jacquinot, and M. Bures.
1D12. Physics Basis for Compact Ignition Experiments. L. E. Sugiyama, B. Coppi, and M. Nassi.
1D13. Nonlinear Gyrofluid Equations for 3D Simulations of ITG Turbulence in a Sheared Slab. G. W. Hammett and W. Dorland.
1D14. Field Reversed Configuration (FRC) Equilibrium and Tilt Stability Modification by Energetic Beams. J. W. Cobb, Y. Tomita, T. Tajima, and D. C. Barnes.
1D15. Nonlinear Gyroviscous Force and its Effect on Momentum Balance Equations. J. D. Callen and Z. Chang.
1D16. Comparison Between Numerical Computations of Island Size with the BETAS Code and Other Solutions. O. Betancourt.
1D17. Computational Study of Inertial Range Spectral Transfer by ExB and Polarization Drift Nonlinearities. D. E. Newman, P. W. Terry, and P. H. Diamond.
1D18. Nonlinear Interaction of Radial Eigenmodes in ITG Turbulence. X.-H. Wang and P. H. Diamond.
1D19. Dynamics of Toroidal Electron Drift Wave Turbulence. P. H. Diamond, X.-H. Wang, and H. Biglari.
1D20. Trapped Ion Turbulence in Tokamaks. X. Garbet, L. Laurent, F. Mourgues, J. P. Roubin, A. Samain, X. L. Zou, and J. Chinardet.
1D21. The Second Criterion for a Thermonuclear Reactor and some Possible Ways to Lower It. H. Wang.
1D22. Effects of Interacting Magnetic Islands on Magnetic Topology and Plasma Transport. C. C. Hegna and J. D. Callen.
1D23. Effects of the Electron Temperature Gradient on the Instability due to the Ion Temperature Gradient. C.-B. Kim and W. Horton.
1D24. 3-D MHD Simulations of RFPs Including Self-Consistent Transport. R. A. Nebel and D. D. Schnack.
1D25. Empirical Orthogonal Functions for ITG Turbulence Simulation. R. H. Cohen, G. R. Smith, and A. M. Dimits.
1D26. On Resonant Excitation of High-n Magnetohydrodynamic Modes by Energetic Ions/Alpha Particles in Tokamaks. L. Chen and H. Biglari.
1D27. Guiding Center Diffusion Induced by Stochastic GradB- and Curvature Drifts. J. Vitela, M. Coronado, and A. Z. Akcasu.
1D28. Edge Turbulent Transport Critical Comparisons. D. R. Thayer, P. H. Diamond, G. R. Tynam, and Ch. P. Ritz.
1D29. Electric Field Inhomogeneities and Ion Temperature Gradient Modes in a Sheared Slab. G. M. Staebler and R. R. Dominguez.
1D30. Gyrokinetic Particle Simulation of Impurity Transport. R. A. Santoro, W. W. Lee, and J. V. W. Reynders.

1D31. Gyrokinetic Particle Simulation of Finite-beta Modified Ion Temperature Gradient Drift Instabilities. J. V. W. Reynders and W. W. Lee.
1D32. A New Look at Time Dependent Transport of Magnetic Helicity. R. W. Moses.
1D33. Control Theoretic Techniques Applied to Tokamak Controls. F. J. Helton, J. M. Greene, and J. W. Helton.
1D34. Study of Alfven Wave Instabilities Using a Hybrid Particle-Fluid Code. F. Y. Gang, D. J. Sigmar, and J. N. Leboeuf.
1D35. Stabilizing Tokamak Microturbulence by Driven Poloidal Rotation. A. B. Hassam.
1D36. Simulation and Modeling of Dissipative Drift Wave Turbulence. A. E. Koniges, J. A. Crotinger, W. P. Dannevik, and P. H. Diamond.
1D37. Super Classical Heat and Particle Transport in Fusion Plasmas. R. J. Taylor.

1E SPECIAL SESSION ON NEW DIRECTIONS
8:00 - 10:00pm
Presiding: A. Hasegawa

1E1. Non-Energy Applications of Fusion Research. J. M. Dawson.
1E2. The Plasma Physics of Plasma Processing. L. Shohet.

TUESDAY MORNING

2A Invited Paper
8:30am - 9:20am
Presiding: B. Cohen

2A1. Experiments on Collisionless Reconnection and the Interaction of Current Channels. W. Gekelman.

2B ORAL SESSION
9:30am - 12:30pm
Presiding: W. Tang

2B1. Landau Fluid Equations for Finite Beta Three Species Alfven Waves. C. L. Hedrick.
2B2. Unified Plasma Fluid/Kinetic Equations for Tokamak Microinstability and Turbulence Studies. Z. Chang, J. D. Callen, and J. P. Wang.
2B3. Studies of m=1 Modes in High-Temperature Plasmas with a Four-Field Model. A. Y. Aydemir.
2B4. Rotation Velocity Profile Control by Slow Electromagnetic Waves. T. H. Jensen and A. W. Leonard.
2B5. Fast Electron Transport in Current Drive. K. Kupfer, A. Bers, and A. K. Ram.
2B6. Drift and Diffusive Losses of Alpha Particles Caused by Toroidal Alfven Eigenmodes. D. J. Sigmar and C. T. Hsu.

TUESDAY AFTERNOON

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

2C1. Quasilinear Evolution of the Beam-Plasma Instability in the Turbulent Trapping Regime. D. Escande, I. Doxas, J. R. Cary, and A. Verga.
2C2. Connection between Recurrence Time Statistics and Anomalous Transport. G. M. Zaslavsky and M. K. Tippett.

2C3. The Unstable l=1 Diocotron Mode in a Hollow Electron Column. S. N. Rasband and R. L. Spencer.
2C4. Linear and Nonlinear Evolution of Resistive Ballooning Modes with Kinetic Corrections. E. Uchimoto and H. R. Strauss.
2C5. Semi-Implicit Gyrokinetic Particle Simulation. T. J. Williams, B. I. Cohen, A. M. Dimits, and L. L. LoDestro.
2C6. Electromagnetic Wave Scattering from Magnetic Fluctuations in Tokamaks. G. Vahala, L. Vahala, and N. Bretz.
2C7. Toroidal Alfven Eigenmodes in a Finite Pressure Equilibrium. F. Zonca and L. Chen.
2C8. Simulation of the Thin Shell and Secondary Shell HBTXIC Experiments. D. D. Schnack and C. G. Gimblett.
2C9. Theory-based Transport Simulations of Tokamak Temperature Profiles. G. Bateman, M. H. Redi, J. C. Cummings, C. E. Singer, and J. Kinsey.
2C10. A quasilinear Description for Fast Wave Minority Heating Permitting Off Magnetic Axis Heating in a Tokamak. P. J. Catto and J. R. Myra.
2C11. A Generalized Deltaf Method. D. C. Barnes.
2C12. Bootstrap Current and Viscous Forces in D-T Plasmas. J. P. Wang and J. D. Callen.
2C13. Spectrum of Turbulent Fluctuations in the Presence of Self-Induced Poloidal Shear Flow. P. W. Terry and P. H. Diamond.
2C14. Feedback Control of the Thermonuclear Thermal Instability with A Poloidal Divertor Suppressor. A. K. Sen, M. Lisak, and D. Anderson.
2C15. Stochastic Broadening in the divertor Region Using the Standard Map. A. Punjabi, A. Verma, and A. H. Boozer.
2C16. Equilibrium Current Profiles in Tokamaks. D. Ernst and B. Coppi.
2C17. Extensions of Neoclassical Transport Theory for Collisional Ions in Strongly-Rotating Tokamak Plasmas. W. M. Stacey, Jr..
2C18. Physics of a Highly Nonequilibrium Ion Distribution: The Polywell/SCIF. N. A. Krall, V. Stefan, and M. Rosenberg.
2C19. Gyrokinetic Particle Simulation of Ion Temperature Gradient Instabilities in 3D Toroidal Geometry. S. E. Parker and W. W. Lee.
2C20. Form Invariance in Convective-Diffusion Systems with Applications. S. M. Mahajan, P. M. Valanju, and W. L. Rowan.
2C21. Ion and Electron Heating in Resistive MHD Turbulence. N. Mattor and P. W. Terry.
2C22. Further Considerations of Large Aspect Ratio High Beta Equilibrium and Stability. S. C. Cowley and R. M. Kulsrud.
2C23. Nonlinear Gyrokinetic Theory of Ion Temperature Gradient Driven Modes with Velocity Shear. T. S. Hahm, W. M. Tang, and M. Artun.
2C24. Analysis of the Particle Diffusion Induced by Stochastic Field Fluctuations Using the Fluid Approach. M. Coronado.
2C25. Comparison of ATF and TJ-II Stellarator Equilibria as Computed by the 3-D VMEC and PIES Codes. J. L. Johnson, D. A. Monticello, A. H. Reiman, A. Salas, and S. P. Hirshman.
2C26. Theoretical Studies of Electron Absorption by Ion Cyclotron RF Fast Waves. P. T. Bonoli and M. Porkolab.
2C27. Alpha Particle Detection by Fully Electromagnetic Thomson Scattering. R. E. Aamodt and D. A. Russell.
2C28. Steady State D-T Burning Tokamak. R. J. Bickerton.
2C29. Calculation of Ideal MHD Growth Rate with Compressibility for Three-Dimensional Stellarator Plasmas. G. Y. Fu, W. A. Cooper, R. Gruber, D. V. Anderson, and U. Schwenn.
2C30. Particle and Energy Confinement Bifurcation in Tokamaks. F. L. Hinton.
2C31. Microscopic Theory and Simulation of Low-Frequency Plasma Motion. P. P. Sosenko, V. K. Decyk, R. D. Sydora, and J. M. Dawson.
2C32. Simulation Study of MHD Relaxation and Reconnection Processes in RFP Plasma. K. Kusano, K. Kunimoto, Y. Suzuki, T. Tamano, and T. Sato.
2C33. Waves in Electron Magnetohydrodynamics (EMH). E. Hameiri.
2C34. Fast Axisymmetric Stability Calculations Using Variational Techniques. S. W. Haney, L. D. Pearlstein, and R. H. Bulmer.

2C35. Nonlinear Magnetohydrodynamics by Galerkin-Method Computation. X. Shan, D. Montgomery, and H. Chen.
2C36. The Force on a Plasma due to an Electromagnetic Wave. A. H. Boozer.

2D POSTER SESSION
4:00pm - 6:00pm

2D1. 2D-Hybrid Particle Model with Non-Linear Electron Distribution. A. Tarditi.
2D2. 3-D Hybrid Kinetic/MHD Simulation for the Energetic Particle Effects. W. Park, S. E. Parker, W. W. Lee, D. A. Monticello, T. S. Hahm, S. C. Jardin, L. Chen, C. Z. Cheng, and R. B. White.
2D3. Radiative Instability in a Diverted Plasma. H. Capes, Ph. Ghendrih, and A. Samain.
2D4. Bootstrap Equilibria in Tokamaks. R. Iacono and A. Bhattacharjee.
2D5. Fluid Model for Bounce-Averaged Trapped Electrons. F. W. Perkins and G. W. Hammett.
2D6. Resistive MHD Studies of TFTR Discharges. M. H. Hughes, M. W. Phillips, S. A. Sabbagh, and R. V. Budny.
2D7. Tokamak Magnetic Islands in the Presence of Nonaxisymmetric Perturbations. A. H. Reiman and D. A. Monticello.
2D8. Spatio-Temporal Chaos in the Saturation of an Unstable Wavepacket. C. C. Chow, A. Bers, and A. K. Ram.
2D9. Particle Transport and Rotation Damping due to Stochastic Field Lines. J. M. Finn, A. A. Chernikov, and P. N. Guzdar.
2D10. Resistive MHD in Tokamak Edge Regions. H. R. Strauss.
2D11. Fueling Effects on Drift Wave Turbulence. A. S. Ware, P. H. Diamond, B. A. Carreras, and H. Biglari.
2D12. Stochastic Diffusion in Two-Dimensional Periodic Flows. I. Doxas, W. Horton, and H. L. Berk.
2D13. Two Dimensional Modeling of Loop and Folded Waveguide ICRF Antennas. D. B. Batchelor, M. D. Carter, E. F. Jaeger, J. S. Tolliver, and R. C. Goldfinger.
2D14. Simulation of Divertor Biasing and Cross-Field Drifts Using the B2 Edge-Plasma Code. T. D. Rognlien, J. L. Milovich, and M. E. Rensink.
2D15. Fluid Model Description of Tokamak Edge Turbulence. L. A. Charlton, J. N. Leboeuf, B. A. Carreras, P. H. Diamond, A. S. Ware, Ch. P. Ritz, and A. J. Wootton.
2D16. Non-Local Effects of Alpha Particles on Second-Harmonic ICRF Heating. O. Sauter and J. Vaclavik.
2D17. Drift Resistive Ballooning Modes and Edge Fluctuations. D. McCarthy, P. N. Guzdar, J. F. Drake, T. M. Antonsen, Jr., and A. B. Hassam.
2D18. Scattering and Localizability of ECH Power in PBX. G. R. Smith, A. N. Kaufman, and D. R. Cook.
2D19. Analytic and Computational Studies of Inertial-Electrostatic Confinement. L. Turner and R. A. Nebel.
2D20. Stochastic Losses of Alpha Particles in Tokamak. J. R. Cary and S. G. Shasharina.
2D21. Numerical Simulation of Drift Wave Turbulence in Fluid Models with Landau Damping. R. E. Waltz and G. D. Kerbel.
2D22. A Self-Consistent Model for Carbon Pellet-Plasma Interaction. L. Vahala, G. A. Gerdin, A. G. ElCashian, and P. B. Parks.
2D23. MFE2 A General-Purpose 2D Moving Finite Element Code for Nonlinear, Time-Dependent Fluid Problems. A. H. Glasser, K. Miller, and N. Carlson.
2D24. Moment Expansions and the Neoclassical Approximation for a Model Kinetic Equation. D. C. Stevens and H. Weitzner.
2D25. Weakly Nonlinear Theory of Multiple-Helicity Resistive Interchange Modes. H. Sugama.
2D26. Properties of c/omega(pe) Filaments. H. Ramachandran, K. Reitzel, G. J. Morales, and B. D. Fried.
2D27. Nonlinear Dynamics of the Toroidal Alfven Gap Mode Driven by the Diffusing Alpha Particles. C. T. Hsu, D. J. Sigmar, B. N. Breizman, and H. L. Berk.
2D28. Nonlinear Dynamic Models Displaying Temporal Features of Sawtooth Oscillations. A. Thyagaraja and F. A. Haas.
2D29. Two-Dimensional Gyrokinetic Simulation Studies. L. L. LoDestro, B. I. Cohen, A. M. Dimits, and T. J. Williams.
2D30. Linear Stability Study of High-n Trapped Electron Modes for the ATF Torsatron. N. A. Dominguez, B. A. Carreras, V. E. Lynch, and P. H. Diamond.
2D31. Steady-state Dynamo and Current Drive in a Nonuniform Bounded Plasma. R. R. Mett and J. B. Taylor.

2D32. Tokamak Transport Driven by Quasineutrality and Helical Asymmetry. P. Garabedian and M. Taylor.
2D33. Relativistic Relationship Between Toroidal Rotation and Charge Density in Tokamaks. E. R. Solano.
2D34. Destabilization of the Toroidicity-Induced Shear Alfven Eigenmode by Alpha Populations Using Fluid Moment Descriptions. D. A. Spong, B. A. Carreras, C. L. Hedrick, N. A. Dominguez, L. A. Charlton, and J. N. Leboeuf.
2D35. Plasma Equilibria as Extremal States. D. Montgomery.
2D36. A Simplified Approach to Pinch Equilibrium. N. A. Salingaros.

BANQUET 6:15 - 10:00pm

WEDNESDAY MORNING

3B ORAL SESSION
8:30am - 10:30am
Presiding: D. Barnes

3B1. Alpha Particle Destabilization of the TAE Modes. C. Z. Cheng.
3B2. Theoretical Structure of Toroidal Alfven Eigenmodes. H. L. Berk, J. Van Dam, and D. Lindberg.
3B3. A Tearing Mode Energy Principle for an Axisymmetric, Finite Beta Configuration. J. M. Greene, M. S. Chu, R. L. Dewar, and A. Pletzer.
3B4. Collisionless Magnetic Reconnection. B. Coppi and P. Detragiache.

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

3C1. Derivation of a Reduced Kinetic Equation Using Lie-Transform Techniques. A. Brizard.
3C2. The LOCUS Interface to the MFE Database. W. H. Miner, Jr..
3C3. Stabilization of Resistive Internal Kinks by Energetic Particles. S. Migliuolo, B. Coppi, and M. Nassi.
3C4. Cyclotron Harmonic Emission from the Generalized Kirchhoff's Law. V. F. Shvets and D. G. Swanson.
3C5. Effect of Drift-Alfven Wave Fluctuations on Internal Resistive Kink. C. Litwin and S. C. Prager.
3C6. Eliminating Vacuum Magnetic Field Asymmetries in Tokamaks. J. D. Hanson.
3C7. General Analysis of Magnetic Loop Positioning for Plasma Control in Ignition Tokamaks. R. R. Khayrutdinov, E. A. Azizov, R. Carrera, J. Q. Dong, and E. Montalvo.
3C8. An Unstructured Second-Order Godunov Method for Transverse MHD. Z. Mikic, D. D. Schnack, I. Lottati, S. Eidelman, and A. T. Drobot.
3C9. Theory and Simulation Study of Surface Waves in Bounded Plasma. X. Q. Xu, G. DiPeso, V. Vahedi, and C. K. Birdsall.
3C10. Presheath and Current-Free Double Layer in a Two-Electron-Population Plasma or a Plasma with Negative Ions. K. Sato.
3C11. Drift Wave Vortices in Inhomogeneous Plasmas and Sheared Magnetic Fields. X. N. Su, W. Horton, and P. J. Morrison.
3C12. Implementing a Fully Implicit Numerical Scheme in a 2-D Fluid Code with the Krylov Method. J. L. Milovich, M. E. Rensink, and T. D. Rognlien.
3C13. MHD Stability Theory Formulated in Terms of a Scalar Representation. E. K. Maschke.
3C14. Map Model for Alpha Particle Containment with Toroidal Alfven Eigenmode. B. N. Breizman, H. L. Berk, and H. Ye.
3C15. Effect of Nonstandard Trapped Particle Orbits on m=1 Perturbations. F. Porcelli, H. L. Berk, and Y. Z. Zhang.
3C16. Gyrokinetic Numerical Simulation Studies of unstable eta(i) Modes. H. V. Wong, K. Jungwirth, and H. L. Berk.

3C17. Alpha Particle Motion in Toroidal Alfven Eigenmodes. H. Ye, H. L. Berk, and V. Yavorskii.
3C18. Computer Simulation of Transport Driven Current in Tokamaks. W. J. Nunan, R. D. Sydora, and J. M. Dawson.
3C19. Tokamak Formation and Sustainment by Tokamak Injection. R. Farengo and T. R. Jarboe.
3C20. Ideal Instability of Shear Flow with Magnetic Field. X. L. Chen and P. J. Morrison.
3C21. Optimum Theory for the Energy Dissipation in a Pinch. C. Y. Wang and A. Bhattacharjee.
3C22. Studies of the Deformable Effects on the Feedback Stabilization of Axisymmetric Modes in Tokamak Plasmas. D. J. Ward, F. Hofmann, and S. C. Jardin.
3C23. Tokamak Rotation and Charge Exchange. R. D. Hazeltine, W. L. Rowan, E. R. Solano, and P. M. Valanju.
3C24. Neoclassical Transport Coefficients for Tokamaks with Bean-Shaped Flux Surfaces. C. S. Chang and S. M. Kaye.
3C25. A Numerical Method for Solving Reaction Rate Equations. R. G. Berger.
3C26. Momentum and Energy Transport due to Long-Range Collisions between Energetic Electrons. A. A. Ware.
3C27. Nonlinear Dynamics of Energetic Ion/Alpha Particle Destabilized. H. Biglari and P. H. Diamond.
3C28. Vortex Filament Dynamics of Hydrodynamics and Magnetohydrodynamics. Y. H. Ichikawa, T. Tajima, R. M. Kinney, and V. I. Petviashivili.
3C29. Theoretical Studies on the Edge Plasma Turbulence in the TEXT Experiments. Y. Z. Zhang and S. M. Mahajan.
3C30. MHD Stability Properties Expressed in Terms of Plasma Profile Characteristics. J. Manickam, S. A. Sabbagh, and H. Takahashi.
3C31. Two Dimensional Particle Simulations of rf-Driven Plasma Sheaths. S. Riyopoulos, W. Grossman, A. T. Drobot, and M. Kress.
3C32. On Edge-Localized Modes. Y.-T. Lau.
3C33. Electron Thermal Transport in High epsilon beta(p) Plasmas in TFTR. J. Kesner.
3C34. Boundary Larmor Radius Effect on Electrostatic Waves. J. Li and J. Scheffel.
3C35. The CQL3D Fokker-Planck Model for Tokamaks. R. W. Harvey, M. G. McCoy, G. D. Kerbel, and G. R. Smith.

Spectra of Drift-Wave Turbulence

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The central question of drift-wave turbulence is describing the transport in $\underset{\sim}{k}$-space of the wave energy from small to large scales. This transport process is mostly through weak-turbulence interactions which justifies a complete study of the weak-turbulence spectral balance equation. The talk is a summation of the analytic results of the predictions from weak turbulence spectral balance theory of drift waves obtained during the last three years.[1,2] The studies include:

1. Finding the new motional invariant governing the direction of turbulent energy flux in $\underset{\sim}{k}$-space,

2. Finding the Kolmogorov-type fluctuation spectra and the analysis of their stability,

3. Developing the non-local weak-turbulence mode coupling model, describing the direct transport of wave energy to large scales. The interaction of the weak turbulence fluctuation components and the vortex-soliton components is also discussed.

[1]A.M. Balk, V.E. Zakharov, S.V. Nazarenko, *On Nonlocal Turbulence of Drift Waves*, Zh. Eksp. and Teor. Fiz **96**, 446 (1990).

[2]A.M. Balk, S.V. Nazarenko, and V.E. Zakharov, *On the Nonlocal Turbulence of Drift-Type Waves*, Phys. Lett. A **146**, 217 (1990).

RELATING TURBULENT FLUCTUATIONS AND RADIAL ELECTRIC FIELDS: A DRIFT WAVE TURBULENCE MODEL*

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A layer of sheared poloidal velocity (or radial electric field) exists in the edge region of many toroidal devices. The presence of this layer has been associated with a reduction in the local level of turbulent fluctuations. This relationship can be a tool for increasing our ability to understand and to control edge fluctuation levels and transport. We have sought basic insights into this relationship using a model based on a familiar paradigm: drift wave turbulence. The underlying instability is the dissipative trapped-electron mode (DTEM). As a simplification, all the relevant nonlinear and electric-field effects have been combined into a single equation.

This (relatively) simple form makes analytic predictions possible. In general, the presence of a sheared flow causes a change in the turbulent decorrelation time which can be associated with a decreased fluctuation level. For this model in particular, it is possible for the fluctuations to generate a mean poloidal flow, given certain conditions.

We have undertaken a numerical test of these results with a highly-resolved radial grid, enough Fourier modes to ensure proper damping, and no additional perpendicular viscosity. The basic DTEM model saturates at a turbulent fluctuation level of a few percent. Although this is about five times the mixing-length estimate, the scaling with the density-gradient scale length is consistent with such an estimate. When a constant, sheared mean flow (or electric field) is introduced, the linear growth rate decreases, in good agreement with the analytic dispersion relation. The fluctuation level in the nonlinear saturated state is reduced. With no imposed flow, but evolution of mean quantities, a sheared, mean poloidal flow appears. A comparison with the analytic predictions is under way.

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

The Mechanism of Self-sustainment in Collisional Drift-wave Turbulence

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Although collisional drift waves in a sheared slab configuration are linearly damped, it is found that the corresponding turbulence is self-sustaining if intialised at nonlinear amplitude. The influence of the free energy source represented by the temperature and density gradients on the turbulent system involving bi-directional spectral energy transfer is responsible for this change of regime, manifested through an indetifiably self-organised mode structure. Fluctuation mode widths are determined by a competition between turbulent advective broadening and parallel dissipation. All of the features of nonlinear mode structure are thereby determined by nonlinear processes, divesting linear stability criteria of their relevance to that structure, or its amplitude. Detailed study with the computations suggests:

a) The threshhold amplitude for nonlinear self-sustainment is somewhat less than ρ_s/L_n, weakly dependent on parameters.
b) In the 2D slab, increasingly strong temperature gradient relative to density exacerbates collisional dissipation, introducing a nonlinear stability boundary. Cases run with temperature gradient just smaller than the limit take longer for self-organisation to get set up, allowing a direct link between this and enhanced free-energy access to be established.
c) Effects of neigboring rational surfaces are judged through the overlap criterion, which shows that the self-organised part does not overlap, but the free-energy tapping part does, leading to the expectation that gradients can be maintained in the tokamak, and that much of the small-scale side of collisional dissipation should be suppressed, enhancing the turbulence in the tokamak edge.
d) The introduction of $\vec{E} \times \vec{B}$ shear flows with gradients as large as c_s/L_n does not suppress this turbulence, but nonlinearly enhances it for strong enough shear (c_s/L_n).

Many important features of experimentally observed tokamak edge fluctuations are reproduced by these single-rational-surface nonlinear dynamics. Consequently, one must continue to consider drift-wave turbulence as a plausible mechanism behind such observations.

3D NONLINEAR DRIFT RESISTIVE BALLOONING MODE-INDUCED TRANSPORT AND POLOIDAL ROTATION

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A 3D nonlinear code has been developed to study the evolution of electrostatic ballooning modes in tokamak edge plasmas. We have found that for these modes with finite diamagnetic propagation, there is self consistently generated mean poloidal flow. The build up of the flow causes the stabilization of the fluctuations. This spin up mechanism is different from the Stringer mechanism[1] and is related to the nonlinear Reynolds stress.[2] In the absence of diamagnetic propagation there is no generation of mean flow. Magnetic pumping is presently being incorporated into the code. With the inclusion of toroidal effects associated with the Stringer spin-up, all of the necessary ingredients for an H mode transition[1] will then have been modelled and a comparison between the two spin up mechanisms will be studied.

1. A. Hassam, T. Antonsen, J. Drake, and C. S. Liu, Phys. Rev. Lett. **66**, 309 (1991).

2. P. H. Diamond and Y. B. Kim (Preprint).

Work supported by the Department of Energy.

1991 SHERWOOD FUSION THEORY CONFERENCE, SEATTLE

NEOCLASSICAL POLOIDAL AND TOROIDAL ROTATIONS IN TOKAMAK PLASMAS

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Explicit expressions for the neoclassical poloidal and toroidal rotation speeds of primary ion and impurity species are derived[1] via Hirshman and Sigmar's moment approach. The rotation speeds of the primary ion can be significantly different from those of impurities in various interesting cases. The rapid increase of impurity poloidal rotation in the edge region of H mode discharges in tokamaks can be explained by a rapid steepening of the primary ion pressure gradient. Depending on ion collisionality, the poloidal rotation speed of the primary ions at the edge can be quite small and the flow direction may be opposite to that of the impurities. This may cast considerable doubts on current L to H bifurcation models[2,3] based on primary ion poloidal rotation only. Also the difference between the toroidal rotation velocities of primary ions and impurities is not negligible in various cases. In Ohmic plasmas, the parallel electric field induces a large Spitzer impurity toroidal rotation close to the magnetic axis, which seems to agree with experimental observations. In the ion banana and plateau regime, there can be a nonnegligible disparities between primary ion and impurity toroidal rotation velocities due to the ion density and temperature gradients.

Poloidal component of viscous force is calculated and it is shown[4] to have a completely different expression from that of K. C. Shaing.[2] Moreover the poloidal flow is shown to be independent of the radial current induced by ion-orbit-loss in steady state. These cast considerable doubts on L-H transition mechanism proposed by Shaing.

Poloidally asymmetric part of neoclassical radial transport fluxes are derived[5] in tokamak plasmas in all collisionality regimes with arbitrary aspect ratio. Asymmetric banana-plateau part (induced by poloidal magnetic pumping) are shown to be much larger than the usual symmetric part by a factor of $\sim 2/\epsilon$. Implications of these asymmetric fluxes on poloidal flow spin-up[3], convective transport of toroidal momentum and enhanced neoclassical transport in the edge region are disscussed.

[1] Y. B. Kim, P. H. Diamond, R. J. Groebner, (submitted to Phys. Fluids).
[2] K. C. Shaing, E. C. Crume, Jr., Phys. Rev. Lett., **63** 2369 (1989) and K. C. Shaing, et. al., Phys. Fluids, **B 2** 2847 (1990).
[3] A. B. Hassam, T. M. Antonsen, Jr., J. F. Drake, C. S. Liu, Phys. Rev. Lett. **66** 309 (1991).
[4] Y. B. Kim and F. L. Hinton, (submitted to Phys. Fluids Lett.).
[5] Y. B. Kim, (submitted to Phys. Fluids).

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Anomalous Transport by Percolation

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The test particle transport due to specified electromagnetic perturbations is discussed within the framework of the guiding center motion,

$$d\mathbf{r}/dt = v_{\|}\hat{\mathbf{z}} + (c/B)\nabla\Psi(\mathbf{r}_\perp, z, t) \times \hat{\mathbf{z}} \ , \tag{1}$$

where $\Psi = (v_{\|}/c)A_z(\mathbf{r},t) - \phi(\mathbf{r},t)$ includes both electric, $\mathbf{E} = -\nabla\phi$, and magnetic perturbation, $\delta\mathbf{B}_\perp = \nabla A_z \times \hat{\mathbf{z}}$. Several regimes of cross-field stochastic transport due to Eq. (1) may be simply mapped to a fundamental problem of 2D turbulent diffusion [1] described by the random time-dependent stream-function $\psi(x,y,t) = (c/B)\Psi(\mathbf{r}_\perp, z(t), t)$:

$$d\mathbf{r}_\perp/dt = \mathbf{v}(\mathbf{r}_\perp, t) \equiv \nabla\psi(x,y,t) \times \hat{\mathbf{z}}. \tag{2}$$

It is shown that different regimes of anomalous transport drop into two main categories. In the *quasi-linear limit*, which takes place for small perturbations, the local turbulent diffusion coefficient is known to scale as $D_T \propto \Psi^2$. In the opposite case of large amplitude, which corresponds to the fast rotation of "fluid elements" in the slowly varying flow (2), the transport is sensitive to the topology of contours of constant value $\Psi(\mathbf{r},t)$ [2]. In this regime, *the percolation theory* [3] is used to describe the long flights of particles along the critical level contours. The percolation scaling for the diffusivity $D_T \propto \Psi^{7/10}$ is then derived. The self-similar nature of large contours of a random function leads to the conjecture that the transport in the nonquasilinear limit is concentrated on fractal sets.

The percolation regime applies to the edge turbulence of tokamak where it may explain the lack of Ψ^2 scaling of the edge transport [4].

The work was supported by U.S. Department of Energy.

References

[1] A.V. Gruzinov, M.B. Isichenko, and J. Kalda, Sov. Phys. JETP **70**, 263 (1990).

[2] M.B. Isichenko, to appear in Plasma Phys. Contr. Fusion.

[3] D. Stauffer, Phys. Rep. **24**, 2 (1979)

[4] Ch.P. Ritz *et al.*, Phys. Rev. Lett. **65**, 2543 (1990).

Atomic Mass Scaling in the Drift Wave Model

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Anomalous transport in tokamaks is widely believed to be driven by a combination of trapped electron and ion temperature gradient (ITG) mode turbulence in the bulk plasma. The theoretical transport models are generally based on the assumption of pure plasmas, with little consideration given to the role of impurities in transport processes. One of the unresolved problems for this interpretation of anomalous energy transport is the absence of any appreciable atomic mass scaling in the predicted energy confinement time. Indeed, in nearly all pure plasma transport models, the ion mass never explicitly appears and enters only through the finite Larmor radius parameter $k_\theta \rho_s$ and the sound speed, c_s. This results in the standard drift wave scaling of diffusivity, $\chi \propto c_s \rho_s^2 / a$ which (at fixed power or temperature) exhibits unfavorable mass scaling; accounting for temperature variation in χ essentially eliminates all mass scaling. However, with the introduction of an impurity ion species, the primary ion atomic mass becomes an explicit parameter in the drift wave transport model, appearing in the combination m_i/m_I with $m_{i(I)}$ the primary (impurity) ion mass. With this motivation, we have incorporated impurity ion dynamics into a numerical stability analysis of electrostatic drift waves in a sheared slab model. Of particular interest is the impurity modified ITG mode (with $T_e = T_i$), which is found to have growth rates inversely proportional to the primary ion mass for $1.2 \leqslant Z_{\rm eff} < 2$; for $Z_{\rm eff} \geqslant 2$, the ITG mode is generally stable is the bulk plasma (assuming the $Z_{\rm eff}$ profile is flat). It should be noted that the stabilization at higher $Z_{\rm eff}$ could be related to improved confinement in deuterium plasmas since a correlation between increasing atomic mass and increasing $Z_{\rm eff}$ is sometimes observed [1]. However, isotope scaling has also been reported in ASDEX [2] in rather pure plasmas ($Z_{\rm eff} \simeq 1.3$). Using quasilinear theory, it is shown that ITG mode turbulence in low $Z_{\rm eff}$ plasmas, $Z_{\rm eff} = 1.2$ and 1.5 (typical of high density ohmic plasmas) obtains energy confinement time scaling with atomic mass number A of the primary ion species, $\tau_E \propto A^\beta$ with $\beta \simeq 0.6$. Preliminary results suggest that a similar conclusion obtains for electron drift wave turbulence in low density ohmic plasmas where $T_e \gg T_i$ and $Z_{\rm eff} \gg 1$. Finally, it should be observed that in the edge plasma region the $Z_{\rm eff}$ profile may have significant radial variation, which can also lead to mass dependence for the ITG mode, if again we assume that $Z_{\rm eff}$ is correlated with the primary ion atomic mass.

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

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[2] F. Wagner *et al.*, EPS (1989), Vol. 13B, part 1, p. 195.

Evidence of Stochastic Diffusion across a Cross-Field Sheath due to Kelvin-Helmholtz Vortices

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Abstract

Our objective is to identify the mechanisms for particle transport across a cross-field sheath. We present a study of $\mathbf{E} \times \mathbf{B}$ motion in a vortex in which the ions are perturbed by the finite gyroradii and electrons are perturbed by one or more traveling waves. Large scale vortices which are the result of a shear in the $\mathbf{E} \times \mathbf{B}$ drift velocity have been observed in plasma simulations of the cross-field sheath[1−3]. Small scale turbulence is also present. The vortices are the result of the nonlinear saturation of the Kelvin-Helmholtz instability. A vortex alone does not allow for the observed electron transport because the electron drift orbits simply circulate. On the other hand, the ion motion can be stochastic from resonant interaction between the drift motion and the gyromotion, independent of the background turbulence. The fluctuations in the ion density would then give rise to small amplitude wave spectrum. The combined action of the vortex fields and traveling wave fields on the electron motion can again lead to stochasticity. We study these effects, showing that the values of vortex fields, observed in the simulation, are sufficient to lead to both ion and electron stochastic diffusion. Furthermore, the rate of the the resulting diffusion is sufficient to account for the diffusion observed in the simulation.

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Three-Dimensional Particle Simulation of Ion Temperature Gradient Mode on Massively Parallel Computers*

Y. Matsuda, T.J. Williams, and J. Byers

Gyrokinetic particle simulations[1] have proven to be a useful method for studying low frequency waves such as drift waves and the associated transport which may be responsible for the anomalous particle and energy transport in tokamaks. One can perform particle simulations with time steps longer than the cyclotron period and fewer particles than in conventional particle simulations because cyclotron motion of particles and fluctuations in the cyclotron frequency range are analytically eliminated while the finite Larmor radius effects are retained. This efficiency improvement would make it possible to simulate plasmas with realistic parameters on a transport time scale. At present, however, it still takes 50 to 100 hours of CPU time on a single processor of the Cray-2 to follow several oscillations of drift waves with a three-dimensional gyrokinetic electrostatic slab code. Clearly, it is necessary to improve the efficiency further. One approach to further efficiency gain is use of a massively parallel computer, and the other is to devise new algorithms that may allow even larger time steps in the simulation. We report our efforts and progress based on the first approach with a three-dimensional electrostatic slab code originally developed by Sydora (with partial support from Lee). Our goal is first to port the three-dimensional code to the Connection Machine - 2, and then use the improved version to study ion temperature gradient mode with more realistic parameters such as scale lengths than have been used so far. We have ported the code to the CM-2 and parallelized the main loop, i.e., charge accumulation, potential calculation, force calculation, and particle pushing. The code at present employs adiabatic electrons and makes use of a multiple-scale expansion. The preliminary results indicate that the CM-2 code when run on 64k processors is 2 to 4 times faster than the Cray-2 code on a single processor. Further work is in progress to optimize the CM-2 code. We also present progress on implementation of the same three-dimensional code on a 128-node BBN TC2000. We use the PFC/PCP split-join parallel programming system[2], and we employ methods developed in our porting of a one-dimensional conventional PIC code to the machine. The results of the efficiency gain as well as the study of ion temperature gradient mode will be reported.

*Work performed for the US DoE by Lawrence Livermore National Laboratory, under contract No. W-7405-ENG-48.

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2. E.D. Brooks III, UCRL-99673, LLNL (1988).

Pressure Driven Collapse of Magnetic Islands and H-MODE in Tokamaks*

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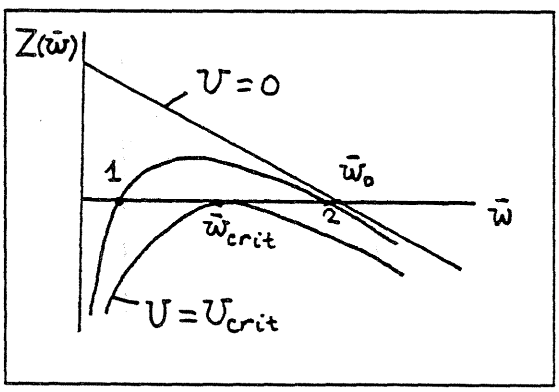
and Kurchatov Institute of Atomic Energy, Moscow, USSR

Equilibrium configurations with finite magnetic islands are considered for circular cross section tokamaks. An equilibrium condition is derived by a quasilinear approximation with respect to the island width, when an equilibrium is established due to a modification of the current profile by the islands. All the parameters determining the equilibrium are taken into account. The resulting relationship gives the island width $\bar{w} = w/\rho_{m/n}$ as a root of the equation

$$Z(w) = \rho_{m/n}\Delta'_w - A\bar{w} - 1.35\frac{U}{\bar{w}} = 0 \qquad U = \frac{8\pi p' \rho_{m/n}}{B_s^2(\rho\mu'/\mu)^2/4}(1-q^2) \tag{1}$$

where $\rho_{m/n}$ is the radius of the resonance magnetic surface, A is a coefficient depending on the current distribution near the magnetic island, p is the pressure, $\mu = 1/q$ is the rotational transform, B_s is the toroidal magnetic field, and Δ'_w is the tearing mode stability parameter being calculated for the current density profile averaged over poloidal angle.



Roots of the equilibrium Eq. (1) for $U > 0$

At $q^2 > 1$, additionally to the unperturbed equilibrium without magnetic island, Eq(1) gives two roots $\bar{w}_1, \bar{w}_2$ for the island width. The largest root is stable and evolutionally connected with the "initial" island width, $\bar{w}_0$ in configuration without pressure. When pressure gradient rises up to the critical value $U_{crit} = 3/16 w_0 \rho\Delta'$, the roots of Eq.(1) join each other

$$\bar{w}_1 = \bar{w}_2 = \bar{w}_{crit} = \frac{1}{2}\bar{w}_0 \tag{2}$$

Above that critical pressure gradient the only equlibrium configuration is the unperturbed one without magnetic islands.

In particular, the tearing mode $m/n = 2/1$, which is unstable in tokamaks, may disappear abruptly during the plasma heating, even at $\beta_{pol} < 1$, that corresponds to an improvement in the energy confinement. That clearly correlates with the disappearence of the Mirnov oscillations at the L- to H-mode transition in experiments.

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

ICRF Coupling at Low Edge Densities

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In DIII–D and other machines, a low edge density often exists at the scrape-off layer during H–mode discharges. Sometimes these densities can be low enough that a lower hybrid resonance layer can be present at the edge. The coupling of the antenna to the slow and fast branches in such a plasma is different from that in a plasma with a higher density pedestal [1,2]. In this paper, ICRF coupling at low edge densities is studied using a cold plasma model. The singularity near the lower hybrid resonance is analyzed. A numerical code is developed, and coupling to the fast and slow branches is studied for different antenna configurations. The results will be discussed and compared with experimental results from DIII–D. The possible effects of septum partitions on the launched spectrum will be discussed.

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Ideal MHD Stability of High Poloidal Beta Equilibria in TFTR†

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Recent experiments in TFTR have expanded the operating space of the device to include plasmas with values of $\varepsilon\beta_{p\ dia} \equiv 2\mu_o\varepsilon<p_\perp>/<<B_p>>^2$ as large as 1.6, and Troyon normalized diamagnetic beta $\beta_{N\ dia} \equiv \beta_{t\perp}\ aB_t/\ 10^{-8}I_p$ as large as 4.7.[1] At values of $\varepsilon\beta_{p\ dia} \geq 1.3$, a separatrix was observed to enter the vacuum vessel, producing a naturally diverted discharge.[2] Plasmas with large values of $\varepsilon\beta_{p\ dia}$ were created with both the plasma current, I_p, held constant and with I_p decreased, or ramped down, before the start of neutral beam injection. In contrast, values of $\beta_{N\ dia}$ that exceeded 2.7 (the nominal upper limit for TFTR supershot plasmas[3,4]) were obtained only when neutral beam heating was applied just after, or near the completion of a fast decrease (-2.5 MA/sec) in I_p. A convenient characterization of the change in I_p using experimental parameters can be defined by the ratio of I_p before the ramp down, to I_p during the neutral beam heating phase, F_{I_p}. The experimental data shows that $\beta_{N\ dia}$ is an increasing function of F_{I_p}.

The ideal MHD stability of these equilibria is investigated to determine their location in stability space, and to study the role of plasma current and pressure profile modification in the creation of these high $\varepsilon\beta_p$ and β_N plasmas. The evolution of these plasmas is modelled from experimental data using the TRANSP[5] code. Two-dimensional equilibria are computed from the TRANSP results and used as input to both high and low-n stability codes including PEST.[6] The high $\varepsilon\beta_p$ equilibria, which generally have an oblate cross-sectional shape, are in the first stability region to high-n ballooning modes. At constant I_p, these equilibria generally have maximum pressure gradients near the magnetic axis and are stable to n=1 modes without a stabilizing conducting wall. High β_N equilibria in which I_p is ramped down ($F_{I_p} > 1$) exhibit peaked current profiles, and those with the largest F_{I_p} have unusually flat pressure profiles near the magnetic axis. The effect of the current profile shape on the stability of low-n kink/ballooning modes and the requirements for these plasmas to access the second stability region will be examined.

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†*Work supported by US Deparment of Energy.*

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REDUCTION OF TOKAMAK ION TRANSPORT IN THE BANANA REGIME BY ORBIT SQUEEZING*

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It is shown that tokamak ion transport in the banana regime is reduced in the presence of a strong shear in the radial electric field as is often observed in the edge region. We allow $\rho_{pi}|dlnE_r/dr| \gg 1$, while assuming $c|E_r|/B_p v_{ti} < 1$ for simplicity. Here, ρ_{pi} is the ion poloidal gyroradius, E_r is the radial electric field, B_p is the poloidal magnetic field strength, v_{ti} is the ion thermal speed, and c is the speed of light. The kinetic theory for the ion distribution function is developed and shown to resemble the kinetic description of transport in a bumpy torus. It is then found that ion thermal conductivity χ_i is reduced by a factor of roughly $S^{-3/2}$, where $S = |1 - (\rho_{pi} dlnE_r/dr)(cE_r/B_p v_{ti})|$ is the squeeze factor. This result reflects more than simple orbit squeezing: the fraction of trapped ions is also modified by S.

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March, 1991

Studies of the Finite Amplitude η_i-Mode [a]

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A modified system of fluid equations describing the instability of the η_i-mode is studied analytically. It differs from the standard system[1] by inclusion of the polarization drift divergence in the pressure dynamics equation, so that the entropy density $S \equiv \ln(P/n^{\Gamma})$ satisfies $dS/dt = -\Gamma \mathbf{v}_D \cdot \nabla \ln T$ and is conserved in simple cylinder or slab models. Here Γ is the adiabatic constant and $\mathbf{v}_D$ is the toroidal drift velocity.

In the limit $(L_n/L_s)^2 \ll 1$ the system is selfconsistently reduced to only two equations depending on only one dimensionless parameter of the equilibrium

$$\hat{\epsilon} \equiv \frac{(1+\eta_i-\Gamma)}{(1+\eta_i)(1+\Gamma T_i/T_e)^2}\left(\frac{L_s}{L_n}\right)^2 \sim 1.$$

This allows us to find the saturated levels of fluctuations and the scaling of the turbulent heat conductivity up to one unknown function of $\hat{\epsilon}$, which describes the effective position of the system above the threshold of instability, $\hat{\epsilon}_{cr} = 0.25$. Close to the threshold the behavior of these functions is found.

The effect of parallel viscosity and heat conductivity on the turbulent transport is investigated. For typical values of these parameters, consistent with estimates from kinetic theory, the cross-field transport is inversely dependent on the parallel one (since it limits the fluctuations of temperature).

The analytic study of the bifurcation in the η_i-mode equilibrium is attempted. In the regime $\hat{\epsilon} \leq 6$ only two radial modes are unstable while there is a broad spectrum in k_y, and thus the process is highly anisotropic. We introduce a truncated system of Ginzburg-Landau-like equations, which describe the interacting wave packets in y-direction.

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FLUID/KINETIC MODELS FOR ALPHA PARTICLE INDUCED INSTABILITIES

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The hot α-particles that are produced in a burning tokamak fusion plasma can significantly affect the stability of the background MHD activity. In particular, the toroidicity induced shear Alfvén eigenmode, or TAE, has been shown to be linearly destabilized by an energetic particle distribution such as might arise from α-particles in a burning plasma, or an injected beam. This mode has been called the gap mode, since its real frequency lies in a toroidicity induced gap in the usual Alfvén continuum. The nonlinear evolution of this mode is unknown at this time. In order to determine the hot α-particle influence on overall tokamak plasma confinement, it is important to assess the nonlinear consequences of the TAE in conjunction with the background MHD plasma. We have recently identified the stable TAE in nonlinear, three-dimensional, toroidal MHD codes. These codes have been modified to include the effect of an energetic species on the usual MHD evolution. Several models for the description of the beam dynamics have been considered, including fluid moment equations, a linearized gyrokinetic model, and full particle dynamics. In this paper we describe the coupling of the particle dynamics with the nonlinear MHD model. These methods have been previously successfully applied to FRC and RFP plasmas. Full details of numerical algorithms, and initial results pertaining to the TAE mode, will be presented.

Nonlinear Dynamics of the Relativistic Standard Map*

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Heating and acceleration of charged particles by RF fields have been extensively investigated by the standard map (ST). Thus, it is natural to pose the question asking how the relativistic effects change the nonlinear dynamical behavior described by the classical ST map. We show that the speed of light limits the rate of advance of the phase in the relativistic standard map (RST) and introduces KAM surfaces persisting in the high momentum region. The RST map is a two parameter (k, $\beta = \omega/kc$) family of dynamics reducing to the ST map when $\beta \to 0$. For $\beta \neq 0$ the relativity suppresses the onset of stochasticity. Chernikov et al. has also reported this effect.[1] We have carried out extensive studies of nonlinear dynamics of the RST map and found very intricate structure of mixing of the higher order periodic orbits and chaotic orbits. We have shown that no matter how it gets chaotic the symmetry properties of the RST map determines its nonlinear dynamical behavior.

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COLLISIONLESS RECONNECTION AND THE SAWTOOTH CRASH

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A model of the sawtooth crash is presented in which electron inertia combined with anomalous diffusion of the current replace classical resistivity in allowing magnetic reconnection to occur.

Experimental measurements of the sawtooth crash time τ_c in the TFTR and JET tokamaks range from 20–2000 μsec.[1,2] The crash time, based on a Sweet=Parker model of reconnection by the $m = 1$ tearing mode, is of order 2000 μsec, which is short enough to explain the slow crashes, but not the fast crashes.

In this paper we show 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 iinertia in Ohm's law allows reconnection to proceed. We present numerical simulations which demonstrate that the current layer during collisionless reconnection using this new Ohm's law collapses to a thickness which is much smaller than the electron collisionless skin depth $\delta = c/\omega_{pe}$, contrary to conventional scientific wisdom. This narrow current layer throttles the nonlinear reconnection rate and, as a consequence, inertial reconnection cannot, by itself, cause the fast sawtooth crash. The extremely narrow current layers induced during collisionless reconnection are strongly unstable to the collisionless current convective instability. We estimate the anomalous current diffusion rate due to this instability to be

$$D_\perp = \rho_e \delta \nabla_\perp v_{\|e}.$$

Electron inertia combined with anomalous current diffusion given by the expression produce sawtooth crash times which are in reasonable agreement with observations.

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A Universal Instability in Fluid Dynamics*

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The analog of the ballooning modes in plasmas is considered for classical fluids. The instability develops along stream lines and may grow in the downstream direction either algebraically or exponentially. This is in contrast to the plasma case where unstable ballooning modes have a fixed spatial structure and grow exponentially in time. We give a mathematical proof to the validity of the WKB description of these modes within the context of the nonlinear fluid evolution equations.

Exact solutions of the ballooning equations are obtained at stagnation points of steady state flows. Remarkably, it is shown that if the flow is smooth at these points, the ballooning modes are always unstable. This result also holds at points where the flow can be observed to vanish in some moving frame of reference which leaves the flow at steady state. Thus, a columnar flow with swirl is ballooning unstable.

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Stabilization of TAE Instabilities via Ion Landau Damping

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The effect of the ion Landau damping on the Toroidicity Induced Alfvén Eigenmodes (TAE) is investigated. By treating each species with a newly derived low-(n, m) drift kinetic solution of the linearized Vlasov equation, a general form of the growth rate of energetic particle Alfvén modes is derived. In particular, the sideband resonance induced by the toroidal curvature is shown to strongly enhance the ion Landau damping on the TAE instability. Also the parameter $\eta_\alpha = d\ln T_\alpha / d\ln n_\alpha$ turns out to be important in the evaluation of the alpha particle driver. For high enough β_i the TAE can be completely stabilized. It is also shown that the ion Landau damping has virtually no effect on the Ellipiticity Induced Alfvén Eigenmodes (EAE). Both the TAE and EAE need further investigation to determine how detrimental their effects may be on alpha particle confinement in ignited tokamaks.

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Mode Conversion in Global Wave Calculations*

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The 1-D theory of the mode conversion at the ion-ion hybrid or second cyclotron harmonic resonances is well developed [1-3]. Inclusion of absorption in the mode conversion process, which is the general situation, necessarily involves extensive numerical treatment even for the 1-D case, where both coupled waves: fast and slow, are considered. In the global wave 2-D or 3-D calculations it is not possible so far to include the full description of the slow wave in the mode conversion analysis. In this situation, mode converted power should be calculated only from fast wave considerations. Here we discuss the possibilities of such calculations and the separation of the mode converted power from the power absorbed by other mechanisms as it included in the code FASTWA. Analysis of the 1-D situation and the generalization for the global wave calculations are given. Comparison with the 1-D code confirm the proposed procedure.

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Quasilinear Driven Transport in a Sheared Flow Field*

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Abstract

The evolution of a passive scalar field is considered for a slowly varying stratified medium which is convected in a turbulent sheared flow. The mode amplitudes are assumed to have an infinite autocorrelation time. Within the quasilinear/random phase approximation, a multiple scale expansion is made. The standard Markovian and continuum approximations are shown to be invalid. For times of order N, where there are $O(N^2)$ excited modes, most of the time dependent perturbation phase mixes away and the fluid reaches a new saturated state with small time oscillations about the temperature. This saturated state has smaller resonance layers, (corresponding to magnetic islands) than occurs in the isolated resonant perturbation case. Thus the quasilinear response to the resonant interactions reduces the effective size of the perturbations. Following homogenisation theory, we find the effective equation for the saturated state. Thus either the quasilinear approximation ceases to be valid on long time scales, or the fluid remains essentially in this modified equilibrium and does not evolve diffusively.

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SHEARED ELECTRIC FIELD-INDUCED SUPPRESSION OF EDGE TURBULENCE USING EXTERNALLY DRIVEN R.F. WAVES

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Here we propose a novel method for active control and suppression of edge turbulence by sheared **E**×**B** flows driven by externally launched RF waves. The theory developed addresses the problem of "flow drive", which is somewhat analogous to the problem of plasma current drive. As originally demonstrated for the case of spontaneously driven flows,[1] a net difference in the gradient of the fluid and magnetic Reynolds' stresses produced by radially propagating waves can drive the plasma flow. For the prototypical case of the Alfvén wave flow drive considered here, $\rho_0 <\tilde{v}_r \tilde{v}_\theta> - <\tilde{B}_r \tilde{B}_\theta>$ is proportional to $k_\perp^2 \rho_s^2$ in the case of the kinetic Alfvén wave, and $[(\eta k_\perp^2 - \nu k_\perp^2)/\omega]^2$ in the case of resistive MHD. Both results reflect the dependence of flow drive on the net stress imbalance. The shear layer width is determined by the waves evanescence length (determined by dissipation) that sets the stress gradient scale length, while the direction of the flow is determined by the poloidal orientation of the launched waves. In particular, it should be noted that both positive and negative E_r may be driven, so that enhanced confinement need not be accompanied by impurity accumulation, as commonly encountered in spontaneous H-modes. The saturated flow velocity is determined by the competition between the wave-induced stress and neoclassical damping. The efficiency is determined by the criterion that the radial electric field shear be large enough to suppress turbulence.[2] For typical TEXT parameters, and unity efficiency, 300 kW of absorbed power is needed to suppress turbulence over 3 cm radially. For DIII-D, 300 kW over 4 cm is needed. It is significant to note that the power requirement is determined principally by the *width* of the suppression zone and not by the *peak velocity shear*. Also, direct transport losses induced by RF have been shown to be small. Extensions of the theory to ICRF are underway and will be discussed. We also discuss the analogous problem of current drive using kinetic Alfvén waves.

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FINITE SHIFT EFFECT ON BALLOONING MODES STABILITY IN A TOROIDALLY ROTATING PLASMA

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ABSTRACT

The widely used s vs α stability diagram for ballooning modes is based on a model that is perhaps the least desirable from the ballooning mode stability viewpoint, that is, the model assumes circular flux surfaces with small shifts, yet has a sufficiently large pressure gradient to drive the ballooning modes. This analysis is extended to include finite shifts of the flux surfaces in a toroidally rotating plasma. It shows that the inclusion of a finite shift leads to a significant further stabilization of the ballooning modes over that from the standard axisymmetrically rotating case.

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Comparison of the Performance of a Fluid Code on Different Machines*

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Studies of the relative performance of the KITE code on different machines will be presented. This performance will be compared with the cost of the machine. 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. It requires over 10^9 floating point operations per time step. The massively parallel version of this code allocates a radial region for each node. In this way, convolutions at a fixed radius are performed in parallel, and communication is limited to boundary values for each radial region. A second parallelization takes place for the block-tridiagonal solves. The Fourier components are distributed in nodes. In each node, the block-tridiagonal matrix is inverted for each of the allocated Fourier components. This code has been implemented on the Cray-II, Cray-XMP, the Intel iPSC/860 Hypercube, and UNIX workstations. Cray-II timings will be shown for both autotasking and single processor runs. Plans for future work include its implementation on the Connnection Machine and the Intel Delta machine.

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EFFICIENT SIMULATION OF HIGH-n TURBULENCE IN BALLOONING COORDINATES[1]

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The high-n ballooning structure ($k_{\|} \ll k_{\perp}$) of many instabilities of interest in tokamak plasmas can be exploited to greatly reduce the computer time required for nonlinear simulations. If V, θ, and ζ are radial, poloidal and toroidal straight-field-line coordinates, then we can use the "ballooning coordinates" V, θ, $\beta \equiv \zeta - q(V)\theta$, with a coarse grid in θ.[2] Here $q(V)$ is the safety factor. The main complication that arises is in the implementation of the correct periodicity conditions $\phi(V,\theta,\beta) = \phi(V,\theta,\beta+1) = \phi(V,\theta+1,\beta-q)$. Three schemes for implementing these periodicity conditions are proposed and studied: 1) By using a grid that has uniform spacing in q and θ (i.e., taking the radial coordinate to be q), the β =const. grid lines at θ and $\theta+1$ can be meshed exactly, without discontinuity. This is the preferred method if the q profile in the region of interest does not become too flat. 2) The fields on β =const. grid lines at $\theta = 0$ can be connected to values obtained by interpolation between grid lines at $\theta = 1$, and vice versa. This method can be used for arbitrary q profiles, but creates a numerical boundary layer at $\theta = 0$ and 1, which must be minimized by careful choices of interpolation scheme and grid spacing in β. 3) In the domain $\theta \in [0,1]$, $\beta \in [0,1]$, we can write $\phi(V,\theta,\beta) = \psi(V,\theta,\beta) + \psi(V,\theta+1,\beta-q)$, where ψ is defined on $\theta \in [0,2]$, and satisfies the boundary conditions $\psi(V,\theta,\beta+1) = \psi(V,\theta,\beta)$ and $\psi(V,0,\beta) = \psi(V,2,\beta) = 0$. While this scheme does not formally give an exact solution to the problem, it may be usable if the quasimodes, of which the linear eigenfunctions are a periodic superposition, are localized to within two poloidal periods.

Results from 3-D fluid simulations of η_i-driven turbulence using method 1 will be presented, along with calculations of the linear ballooning mode structure of some relevant instabilities to test the applicability of method 3. For particle simulations, it is adequate to use a standard (V,θ,ζ) grid and to mask out the modes with $k_{\|}(V) \geq \alpha k_{\theta}$ for some small α, since the increased number of grid points will have little effect on the time taken to do the charge deposition calculations that dominate the computer time used by particle simulations.

[1]Performed by LLNL for USDoE under contract W-7405-ENG-48.
[2]A. H. Glasser, private communication.

STABILIZATION OF DRIFT MODES BY SHEARED PLASMA ROTATION

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The effect of sheared plasma rotation on slab-like trapped electron instabilities is investigated. Both parallel and perpendicular rotation shears are considered. Complete stabilization is found to occur for $|\mathbf{b}\times d\mathbf{V}_0/dr| > C_s/L_s$, where V_0 and C_s are the plasma rotation and sound speed, $\mathbf{b}$ is the unit vector along the magnetic field, and L_s is the magnetic shear length. In particular, we find that the parallel flow-shear driven drift Kelvin-Helmholtz instability is quenched above this threshold, which is easily exceeded in the edge region of H-mode plasmas. Significantly, it also appears to be reached in the confinement region of neutral beam heated plasmas.

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Tokamak Transport Based on the Thirteen Moments Model*

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The two-fluid 13 moment equations are applied to the case of a moderately large tokamak. The 13 moment equations were first applied by Grad to model a rarified gas. In the 13 moments model the stress tensor and the heat flow are given by differential equations instead of by linear relations with the thermodynamic forces of the system. Here a scaling of the variables is assumed and a reduced set of equations is obtained. These equations are written in flux coordinates and an expansion in inverse aspect ration is carried out. The goal of this work is to determine the equilibrium and associated transport and to obtain the evolution of the equilibrium on the transport time scale.

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The Effect of Orbit Averaging on Plasma Turbulence and Turbulent Transport*

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The effect on plasma turbulence of orbit averaging by thermal ions is considered, and illustrated for two modes of potential importance for tokamaks. This effect is complementary to the orbit averaging effect more commonly discussed, in which the averaging modifies the extent to which a given spectrum of fluctuations affects particle motion. Here, the same averaging modifies the extent to which particles affect the fluctuations, as manifested through the susceptibility. The effect can reduce the ion response below that in earlier treatments, modifying the predicted mode growth rate, which in turn modifies the turbulent transport. For both the ion temperature gradient and trapped electron mode (TEM), the effect modifies earlier transport expressions with a 'neoclassical factor,' which makes the scalings of the resultant transport coefficients with plasma current and magnetic field closer to those found experimentally. Additionally, for the TEM, this mechanism provides an explanation of the observed more favorable scaling of χ_i with T_i in supershots than in L–modes.[1]

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WEAK TURBULENCE THEORY OF LANGMUIR WAVES: A RECONSIDERATION OF VALIDITY OF QUASILINEAR THEORY

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The weak turbulence theory of Langmuir waves in a one-dimensional, one-species plasma is discussed. Analytical calculations using the theory of two-point correlation functions[1] show that in the weak turbulence regime $\tau_{ac} \ll \min[\tau_{tr}, \gamma_k^{-1}]$, the nonlinear enhancement of the mode growth rate relative to the linear Landau mode growth rate γ_k^L is rather weak, and quasilinear theory is reproduced at the lowest order. Hence this work also proves the validity of the quasilinear theory. Here $\tau_{ac} \sim (k\Delta v_{ph})^{-1}$ is the phase-mixing time or the auto-correlation time, and $\tau_{tr} \sim (k^2 D^{ql})^{-1/3}$ is the particle decorrelation time or the turbulence trapping time. In particular, the lowest order nonlinear correction to γ_k^L in the regime $\tau_{ac} \ll \tau_{tr} \ll \gamma_k^{-1}$ is proportional to $(\gamma_k^L/\omega_k)\gamma_k^L$, and the corresponding correction for $\tau_{ac} \ll \gamma_k^{-1} \ll \tau_{tr}$ is proportional to $(1/\omega_k \tau_{tr})\gamma_k^L$. Both corrections are additive, not multiplicative, and are of higher order in the weak turbulence expansion. The smallness of the corrections is due to the fact that the only mechanism for the relaxation of the plasma distribution function in a one-dimensional, one-species plasma is momentum exchange between waves and particles, which is exactly the interaction considered in the quasilinear theory. No like-like particle momentum exchange is allowed due to momentum conservation constraints. Thus, we disagree with the result of Adam, Laval and Pesme[2] which indicates a non-negligible multiplicative correction in the regime $\tau_{ac} \ll \tau_{tr} \ll \gamma_k^{-1}$. Similar calculations are also done for the traveling wave tube, which can be used to test this theory experimentally, especially for the case of bump-on-tail instability. A comparison of theoretical predictions with experimental results[3] will be presented.

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Numerical Study of $n = 1$ Stability of PBX-M at High $q(0)$*

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Recent theoretical work [1] has shown that, for tokamak configurations that allow a stable access to the ballooning second stability region with high $q(0)$ and vanishing edge current density, the low-n external modes can also be stabilized at sufficiently high $q(0)$, for any beta up to the equilibrium limit. This has been verified numerically for D-shaped and indented cross sections, using a fixed numerical grid of the PEST code. Here we present a detailed study of the convergence of these results, as the numerical discretization parameters are varied towards their continuum limit. A configuration typical of PBX-M operation with non-inductive current drive and low total current is considered. Fast convergence is observed with respect to the poloidal grid size and the mode cut-off in the poloidal Fourier expansion of the perturbation, provided an arc length poloidal coordinate is adopted. The convergence with respect to the radial grid size is found to be slow, and the appropriate scaling of numerical errors proportional to the square of the grid size must be checked before extrapolating to the zero mesh limit.

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

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Gyrokinetic Particle Simulation of ITG Modes in General Toroidal Geometry

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Abstract

We have generalized the 1-1/2 d linearized gyrokinetic particle simulation code of Xu et. al. [1] to tokamaks with non-circular corss section (i.e. elongation and triangularity) to study ion temperature gradient modes (ITG) in the presence of ion-ion collisions. We hope to determine the role of local magnetic shear, poloidal beta and various geometric factors in linear growth rate and transport coefficients. For comparison to DIII-D, we apply the code with input parameters calculated by the MacEquilibrium Code of Haney [2] using experimental measurements of DIII-D.

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TOROIDAL MICROINSTABILITY STUDIES OF CONFINEMENT TRENDS IN TFTR*

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In examining the possible relevance of toroidal drift-type microinstabilities for tokamaks, attention is here focused on applications of realistic kinetic stability calculations to confinement trends observed in TFTR. The principal theoretical tool used is a comprehensive toroidal code[1] which carries out self consistent, ballooning-formalism eigenmode calculations including all resonances, finite beta effects in the equilibrium as well as the perturbations, and finite trapped-ion banana orbital dynamics, along with FLR effects to arbitrary order. This code has been interfaced with realistic numerical MHD equilibria and physical parameters specific to the TFTR experiments of interest. Results from the calculations of the linear properties and quasilinear fluxes of toroidal drift modes driven by trapped-particle and ion temperature gradient effects indicate the following:

(i) A strong temperature dependence (diffusivity $\propto T^{\alpha}$, with α between 3/2 and 5/2) is found which appears to be consistent with the temperature scaling observed in the confinement region of perturbative transport experiments carried out on L-mode discharges. Dependences on radial variations of equilibrium quantities (density, temperature, safety factor, *etc.*) and their gradients are also explored.

(ii) An important trend observed in TFTR supershot discharges is that, unlike the L-mode cases, confinement actually appears to *improve* with increasing ion temperature. The theoretical results here show that, at sufficiently high T_i ($\gtrsim$ 10 keV), confinement for supershot cases indeed ceases to degrade with increasing ion temperature. Variations with T_e are also examined, and the implications of the results discussed.

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Alfvén Continuum Gap and the High n Gap Mode in a Noncircular Tokamak

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The Alfvén continuum gap for a general cross-section tokamak is computed by solving the coupled Alfvén and sound wave equations [1]. The boundary conditions determined from application of the Floquet theorem characterize the gaps to have an odd or even parity. It is found that torodicity induces the first gap (with odd parity) near frequency $\omega_A/2$, ω_A being the Alfvén frequency at the plasma center. The gap mode at this frequency has been extensively studied [2]. Plasma ellipticity induces the second gap (with even parity) near ω_A. Triangularity induces the third gap (with odd parity) near $3\omega_A/2$, etc. These higher gaps, although at higher frequencies, are still of substantial width when the cross-section shape is highly elongated ($\kappa \sim 1.8$), and highly triangulated ($\delta \sim 0.5$). This can also be significant for a noncircular fusion plasma. The high n gap mode is then determined from the ballooning mode equation with frequency situated inside the gap. The relationship between the high n gap mode and the ballooning mode stability criterion at high plasma β is explored.

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*Princeton Plasma Physics Laboratory, Princeton, New Jersey.

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March, 1991

Ion Transport from Kinetic η_i Modes: Comparisons with Experiment and Fluid Results [a]

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Ion transport from kinetic η_i modes in the slab model is obtained using the low noise δf algorithm. The results are within roughly a factor of 2 of mixing length estimates using gyrokinetic eigenfunctions. Detailed comparisons with transport in L-mode discharges demonstrates that transport from kinetic slab η_i modes is much too small to explain the experimental transport. This conclusion differs from ones reached using fluid calculations of transport. Kinetic Landau damping is found to be very important for experimental parameters. The fluid model overestimates transport by an order of magnitude (or more).

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[a] Work is supported by U.S.DoE.

Comparison of Local and Non-local Kinetic Theory of Ion Temperature Gradient Modes*

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A study using a simple local-kinetic theory[1] has shown that the decreasing q (safety factor) value can give a strong stabilizing effect for the toroidal ion temperature gradient mode. In this local analysis, the full resonance terms $\mathbf{k} \cdot \mathbf{v}_D + k_{\|} v_{\|}$ due to the magnetic curvature drift and the parallel transit drift are retained but the local approximation of $\theta = 0$ is used with $k_{\|} = 1/Rq$. In this work, we solve numerically the non-local gyro-kinetic equation in the ballooning space. From this study we can obtain the shear dependence as well as the more exact q dependence of the growth rate and the threshold of temperature gradient η_c. Comparisons are given between the local and non-local results.

* Work is supported by USDOE.

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1991 SHERWOOD ABSTRACT

Gyrokinetic Simulation of Energetic Particle Effects on Tokamak Stability*

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Low frequency fluctuations, such as drift waves and ballooning modes, can be excited by the presence of fusion produced or injected energetic particles. Most theoretical investigations of these low frequency modes in literature are either based on analytic approximated solution of the gyrokinetic equation or numerical particle simulation technique. An alternate numerical approach to solve the gyrokinetic equation directly has been proposed recently. The advantage of this approach is the inclusion of many important kinetic feature of the problem and realistic geometry without approximations.

The gyro-kinetic equations for the background electrons, ion and energetic particles are written in the time domain form. Ballooning mode representation is employed to reduce the system to a one dimensional spatial problem in the extended poloidal angle variable. The distributions of all species are followed in time from given initial perturbations by solving the time domain gyrokinetic equations with a partially implicit scheme. For unstable modes, the distribution functions will eventually develop to a definite steady growth state independent of the initial perturbations. Both the linear growth rate, the eigenfrequency and eigenmode structure can be determined at this stage. Detailed results of the electrostatic and electromagnetic instabilities due to the energetic particles will be discussed.

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RENORMALIZATION GROUP ANALYSIS OF TWO DIMENSIONAL MHD TURBULENCE

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The renormalization group (RNG) method has been used to analyze the physics of two dimensional (2-D) MHD turbulence. The applicability of the RNG method to 2-D MHD turbulence is based on the universality of the properties of hydrodynamic turbulence in inertial range. After averaging over small scales and performing a scale transformation, it is found that the inertial range spectra have simple scaling forms near the fixed point . The resulting renormalized viscosity shows that the contribution from the small scale velocity field is negative while the contribution from the small scale magnetic field is positive. The negative contribution is related to the inverse cascade of kinetic energy in pure 2-D hydrodynamic turbulence while the positive contribution is symptomatic of the Alfven effect. Meanwhile, the result for the renormalized resistivity indicates that small scale magnetic field acts like a negative resistivity on large scale magnetic field while the small scale velocity field gives a positive contribution. In addition, the exponents for the kinetic and magnetic inertial range spectra given by the RNG are the same. Both of them are proportional to $k^{-3/2}$. All corrections, including those from higher orders of expansion and those from new nonlinear terms created when applying the RNG method, are discussed and are found irrelevant or negligible. Our results are consistent with results from other methods as EDQNM, DIA. Comparisons with the results of such other methods will be presented and the relative strengths and weaknesses of the RNG will be discussed.

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Perturbative transport due to drift wave fluctuations

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We study the anomalous electron transport due to drift-wave turbulence in tokamaks, including both trapped and untrapped electron contributions.

The full transport matrix relating the incremental fluxes of particles and heat due to perturbations in the plasma gradients are obtained from the renormalized response function, using the perturbative method developed in ref.(1), which extends the results of quasilinear theory. In particular, the transport matrix obtained does not obey Onsager symmetry.

In order to relate the full theoretical results with the "effective" empirical laws used to interpret the experimental results, we assume an algebraic relation between the temperature fluctuations and the density fluctuations (justified in the limit of large heat transport coefficients). We use this relation to obtain reduced transport equations, containing only density fluctuations and density gradient fluctuations dependencies. The coefficients of the transport equations depend on equilibrium quantities. Compatibility between theoretical results and experimental results impose constraints on the relation between the density and temperature fluctuations.

We also calculate the impurity transport coefficients, and study their relation with the electron and heat transport.

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Net Transport Equations For A Tokamak Plasma

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We consider a fluid moment (n,T, **V**, **q**) description of a tokamak plasma that allows for kinetically and nonlinearly determined stress tensor and heat stress tensor closure relations. These extended fluid moment equations are the result of the fluid/kinetic hybrid description of plasmas based upon a Chapman-Enskog-like approach that has been developed recently [1]. The flux-surface-average of these extended fluid moment equations yields net "radial" transport equations that include classical, neoclassical and fluctuation-induced transport effects. It can be directly shown from these equations that while the lowest order perturbations with $\mathbf{E} + \mathbf{V} \times \mathbf{B} - (1/nq)\,\nabla p = 0$ cause no net transport for $\nabla n \times \nabla T = 0$, higher order perturbations that include dissipative effects due to plasma resistivity [2] and viscosity can. The net transport equations reduce to the neoclassical transport equations [3,4] in the equilibrium ($\partial/\partial t << \nu$) limit where the fluctuation effects (fluidlike or kinetic) are negligible. In particular, they include the neoclassical bootstrap current, poloidal flow damping, irreducible minimum neoclassical ion heat conduction, and trapped-particle effects on the electrical resistivity, all of which seem to be observed experimentally in tokamaks. In this model turbulent fluctuations induce additional, anomalous transport through friction and viscous stress fluctuations in tokamak plasmas.

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Effect of Drifts on the Diffusion of Runaway Electrons in Tokamak Stochastic Magnetic Fields*

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The quasilinear diffusion of runaway electrons in tokamak stochastic magnetic fields is examined. Previous models are generalized with respect to the spatial location and coherency of the perturbing magnetic fields, treatment of the radial as well as poloidal drift motion of the electrons, and the role of sidebands which arise from the beating of the electron drift motion with the applied perturbing fields. It is found that drift effects act to reduce the level of quasilinear diffusion by an amount that depends on the poloidal distribution of the magnetic turbulence. The results are employed to estimate the internal magnetic fluctuation levels during recent experiments on the TEXT tokamak, where the drift modification effects are shown to be small. It is inferred that intrinsic magnetic turbulence controls runaway diffusion, but not the thermal diffusivity of the background electrons.

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Coupled Energy and Current Transport+

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The redistribution of the current density in a high temperature plasma is usually described in terms of the magnetic field "diffusion" associated with the collisional resistivity relevant to the specific physical and geometrical properties of the plasma. It is generally concluded that the order of magnitude of the time scales involved in the current density redistribution are consistent with the collisional resistive times. Yet there are indications that it should not be sufficient to relate the applied electric field $E_{||}$ to $J_{||}$ through the collisional resistivity η only, in order that the appropriate current density profiles be reproduced. In particular in regimes where a significant fraction of the electron population is trapped and the collisional resistivity is given by the so-called "neoclassical" expression, the resulting current density profile is "strange" if the electron temperature radial profile is close to a Gaussian.

We assume that in ohmic regimes, where the applied electric field drives the current and at the same time heats the plasma, the transport of the electron thermal energy and the redistribution of the current density are strongly coupled. We consider a matrix equation that describes the transport for both quantities under steady state conditions, we postulate symmetry properties of the elements of this matrix and use them to define two transport coefficients: an effective thermal conductivity and a thermal – viscous coefficient[1].

The requirement that the adopted transport coefficients comply with the so-called "profile consistency" and generate acceptable profiles both for the electron temperature and the current density is used together with the experimental observation that the loop voltage lays within a relatively small range of values for the most disparate types of ohmic experiments.

An integro-differential equation is derived from the matrix transport equation and the resulting steady state electron temperature and current density profiles, as obtained from numerical solutions, are presented. We find that the thermal-viscous coefficient leads to a broadening of the current density profile and to an increase of the central electron temperature, while the temperature profile remains largely unchanged [2].

We propose that the degradation that occurs in the presence of injected heating is associated with the decoupling between the thermal energy transport and the current energy transport when the electric field is no longer the source for both. In this case we argue that the contribution to the electron thermal energy diffusion coefficient by collective modes that do not depend directly on the current density distribution becomes prevalent.

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STABILIZATION OF SAWTEETH IN TOKAMAKS BY SHEARED POLOIDAL FLOWS

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The resistive internal kink mode in a current profile with a central safety factor $q(0) < 1$ is shown to be stabilized by sheared poloidal flows. The internal kink mode is found to be stabilized when the local gradient in the poloidal rotation frequency ω at the $q = 1$ resonant surface r_1 is larger than the local gradient in the shear Alfvén frequency $\omega_A = k_{\|}(r)V_A$, where V_A is the Alfvén velocity and the parallel wavenumber $k_{\|}(r) = R^{-1}(1 - 1/q(r))$ with R the major radius of the torus and $q(r)$ the safety factor profile in the minor radial coordinate r; i.e.,

$$|d\omega/dr|_{r_1} \geq |d\omega_A/dr|_{r_1}.$$

The gradient in the shear Alfvén frequency is determined by the shear in the magnetic field at the resonant surface. This criterion for stabilization does not depend at all on the plasma resistivity or on the global details of the poloidal velocity profile and the current profile. The internal kink is stabilized by sub-Alfvénic flows in which the peak velocity is only a very small fraction of the Alfvén velocity. For the high β plasmas of tokamaks like TFTR and JET ($\beta \sim 10^{-2}$), sawteeth are stabilized by sub-sonic flows in which the poloidal velocity is less than the sound speed. The application of perpendicular neutral beam injection in an annulus around the resonant surface can generate the sheared poloidal flow[1] necessary for the stabilization of sawteeth.

1. A. B. Hassam, paper presented at this meeting.

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Examination of Sawtooth Stabilization by Localized Electron Cyclotron Heating Near the $q = 1$ Surface

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Sawtooth oscillations in the Kyoto University WT-3 tokamak are observed to be strongly modified or suppressed by localized electron cyclotron heating near the $q = 1$ surface.[1] It has been proposed that this is due to current profile modification leading to stabilization of the $m/n = 1/1$ resistive mode. In general, a local current density increase occurs due to ECH. This can be attributed to direct current drive and/or an enhanced local conductivity due to localized electron heating. To gain further insight into these phenomena, we use the TORCH code to simulate the electron cyclotron heating and current drive that occurs in WT-3. The tokamak equilibria into which the rf power is launched is generated using the PEST code. We describe the launched electron cyclotron power using a gaussian beam antenna model in order to establish the degree of localization of the electron cyclotron power. The total driven current resulting from the electron power deposition is computed taking into account trapped particle and relativistic effects. The modified current profile is then assessed for its stability properties using the PEST code. In this study, we first concentrate on the wave and parameter space appropriate to the WT-3 experiment to help in the understanding of the experimental results and in the design of new experiments that can distinguish between the different physics mechanisms that play a role in the stabilization of the sawtooth oscillations. We will then consider the applicability of ECH stabilization of sawtooth oscillations in the BPX and ITER tokamaks.

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‡ Supported by a Grant-in-Aid of Scientific Research and the Ministry of Education in Japan.

1 Sawtooth Stabilization by Localized Electron Cyclotron Heating in a Tokamak Plasma by K. Hanada et al, PPPL-2725, Princeton University (to be published in Phys. Rev. Lett.)

Inertia Effects on the Rigid Displacement Approximation of Tokamak Plasma Vertical Motion*

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Elongated plasmas in tokamaks are unstable to axisymmetric vertical displacements. The vacuum vessel and passive conductors can stabilize the plasma motion in the short time scale. For stabilization of the plasma movement in the long time scale an active feedback control system is required. A widely used method of plasma stability analysis uses the Rigid Displacement Model (RDM) of plasma behaviour. In the RDM it is assumed that the plasma displacement is small and usually plasma inertia effects are neglected. In addition, it is considered that no changes in plasma shape, plasma current, and plasma current profile take place throughout the plasma motion.

It has been demonstrated+ that the massless- filament approximation (instantaneous force-balance) accurately reproduces the unstable root of the passive stabilization problem. Then, on the basis that the instantaneous force-balance approximation is correct in the passive stablization analysis, the massless approximation is utilized+ also in the study of the plasma vertical stabilization by active feedback.

We show here that the RDM (without mass effects included) does not provide correct stability results for a tokamak configuration (plasma column, passive conductors, and feedback control coils). Therefore, it is concluded that inertia effects have to be retained in the RDM system of equations. It is shown analytically and numerically that stability diagrams with and without plasma-mass corrections differ significantly. When inertia effects are included, the stability region is more restricted than obtained in the massless approximation .

+ E.A. Lazarus, J.B. Lister, and G.H. Neilson, "Control of the Vertical Instability in Tokamaks", Nuclear Fusion, 30 (1990) 111.

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Gyrokinetic Modeling Including Collisions: Neoclassical Diffusion Studies*

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The gyrokinetic particle simulation model is used to study particle diffusion in a toroidal magnetic field. Previous simulations[1] obtained results in agreement with the existing theory for the banana and plateau regimes, but failed to include the charge separation due to the toroidal drifts(the grad B and curvature drifts), which gives rise to the Pfirsch-Schluter diffusion, and which may also play an important role in the banana and plateau regimes.[2] An electrostatic gyrokinetic code including binary collisions which are energy and momentum conserved[3] is developed to study this charge separation effect on neoclassical diffusion. First, the q dependence of the diffusion coefficient is examined without the inclusion of the self-consistent electric field. It is found that the coefficient varies as q^2 in the banana and plateau regimes, in agreement with the neoclassical theory, and becomes q independent as q gets larger(>5) in the Pfirsch-Schluter regime. Next the charge separation is included by keeping low wavenumber Fourier modes of the electric field in the simulation. Preliminary results show an enhancement of diffusion in the Pfirsch-Schluter regime, and it is found that the dipole moment of the electric potential in the direction of the toroidal drifts is mainly responsible for this enhancement, which agrees with the physical picture of the Pfirsch-Schluter diffusion. These and other results will be presented.

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Nonlinear Evolution of Ion-Streaming Instabilities along Auroral Fields *

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Abstract

Streaming cold ions due to the potential drop along the magnetic field lines in the high latitude Auroral zone is the main free energy source of the instabilities occuring in this region. Both linear and nonlinear behaviour of these streaming instabilities are studied concentrating on parallel subsonic ions of H^+ and O^+ with relative streaming velocity $\Delta v < C_s(H^+)$. Linear analysis shows that for $\Delta v > v_{th}(H^+)$ there exists a critical k_c in wave number space with unstable modes for $k < k_c$ and stable modes above k_c for given free energy $m_H \Delta v^2/2$. Particle simulation using a 1-D quasi-neutral code having massless electrons with full nonlinear adiabatic response are carried out. It is shown that the most unstable short wave length mode in the linear stage breaks and coalesces into long wave length modes with scale length order of several electron debye length in the saturated state. Power spectrum analysis shows that the phase velocities of this long wave length modes are order of the thermal velocities of ion species but rather close to heavy ion species and thus induces significant heavy ion heating. Dynamics of the phase space vortices coalescence is discussed.

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The Structure of Ideal MHD Alfvén Modes

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Continuum Alfvén modes have undergone a resurgence in interest with the recent realization that so-called Toroidicity-Induced Alfvén Eigenmodes (TAE modes) can be destabilized either by energetic beam ions in a strongly heated plasma or by alpha particles in a burning plasma [1,2]. The GATO Ideal MHD Stability code [3], which minimizes the potential energy according to a variational formulation, has now been modified to isolate and calculate stable continuum eigenmodes. The existence of the TAE mode and its associated gap has been verified, using this code, for a circular cross-section, finite aspect ratio equilibrium. Moreover, the eigenfrequencies and eigenmodes obtained from this variational calculation are found to be in extremely good quantitative agreement with those obtained from the non-variational NOVA code [1,2].

A systematic survey of the stable continuum has further revealed a surprising diversity in the structure of the continuum Alfvén modes; the logarithmic singularity can be so broad, in some cases, as to occupy the whole cross-section. This has important implications for heating experiments which aim to locally excite the plasma by rf waves in the Alfvén frequency range. The structure of several representative examples will be discussed. The Alfvén continuum, in general, and the TAE mode and its associated gap, in particular, are also found to be strongly modified by cross-sectional shaping. The dependence of the spectrum on various shaping factors will be explored.

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Ellipticity Induced Alfvén Eigenmodes

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It is shown that noncircularity of tokamak flux surfaces leads to frequency gaps in the magnetohydrodynamic Alfvén continuum. Within these gaps a new class of discrete modes having macroscopic structure is shown to exist that have many common features with toroidicity induced Alfvén eigenmodes. In particular, both can be driven unstable by a small population of high energy alpha particles. Therefore the EAE, as well as the TAE, may play an important role in the design of future ignited tokamaks. Since $\kappa - 1 > \epsilon$ in many tokamaks the ellipticity induced Alfvén eigenmode may indeed be a more robust mode. The most potentially dangerous mode couples the $m = 1$, $n = 1$ and $m = 3$, $n = 1$ "cylindrical" eigenmodes. The region of strong coupling occurs at the $q(r) = 2$ surface and the width of the coupling region is finite, of order $(\kappa - 1)a$. The drift kinetic treatment shows that this mode can be strongly destabilized by transit resonance with energetic alpha particles. The growth rate depends upon a competition between the alpha particle driver and electron and ion Landau damping. Growth rate values for typical ignition devices are presented.

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ICRF ACTION TRANSFER FROM MAGNETOSONIC TO ION BERNSTEIN WAVE*

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Many researchers have concerned themselves with the calculation of the wave action transfer coefficients of the ICRH problem. In most cases the calculations have involved numerical integration of differential equations. We have been working toward a completely analytic derivation of these coefficients. In our slab model, we consider a ray-phase-space (x, k_x) point of view, in which action is converted from an incident *magnetosonic* wave to a continuum of *minority-ion-current* waves indexed by $v_{||}$. These waves propagate primarily in k_x-space and coherently emit the reflected magnetosonic wave as they cross its dispersion surface [1,2]. As they continue to propagate in k_x-space, they leave the region of conversion with the magnetosonic wave and enter a region where an *extraction* process occurs. In this region, the minority-current waves may be expressed as a superposition of *gyroresonant ballistic* waves and a single collective *ion-Bernstein* wave. The gyroresonant ballistic waves propagate only in k_x-space, while the ion-Bernstein wave propagates in both k_x-space and x-space. We extract it from the continuum of gyroresonant ballistic waves by applying the method of Bateman & Kruskal [3]. We are generalizing this analytic method to the more realistic 2D model of axisymmetric tokamak geometry, in which action transfer and wave propagation occur in a four-dimensional ray phase space.

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Efficiency of rf-driven current in a noncircular tokamak*

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The Green's function for current drive by radio-frequency waves in a noncircular tokamak is calculated. This extends the our earlier work for a circular cross-section tokamak [1] to arbitrary axisymmetric equilibria. In particular, we evaluate the efficiency for various Solov'ev equilibria and for a numerically generated ITER equilibrium [3].

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SHERWOOD THEORY MEETING 1991

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

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ABSTRACT

The nonlinear evolution of the tearing mode instability with equilibrium shear flow is investigated via numerical solutions of the time dependent, visco-resistive magnetohydrodynamic equations. The two-dimensional simulations in slab geometry, periodic in x-direction are initiated with solutions of the linearized MHD equations. Magnetic Reynolds number S was varied from 50 to 10^4, the flow parameter V was varied up to 1.0 in units of the average Alfven speed, and small viscosity ($S_v < 10^6$) was incorporated in the model. When the shear flow is small ($V < 0.3$) the tearing mode saturates within 100 Alfven times, while large flows ($V > 0.3$) induce temporal and spatial oscillations of the plasma with a period of ~1 Alfven time regardless of the value of resistivity, viscosity or the size of the physical system in the non periodic direction. They are initiated within 20 - 50 Alfven times and persist through the simulation time ($T > 100$). The initiating time depends on the flow parameter, and the period is affected by the dissipation parameters. Analytical calculations, and close examination of their temporal and spatial evolution, suggest that the oscillations are Alfven waves that originate near the region where the magnetic field and flow are parallel and homogeneous. They propagate towards the resistive layer and are resonantly absorbed in a region of small local Alfven speed outside the resistive layer.

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Numerical Modeling of ICRF Heating and Current Drive*

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Numerical 3-D modeling of ICRF fast wave penetration, power deposition, RF driven and bootstrap currents is presented for the Phaedrus-T tokamak. The power absorbed by different plasma species and different absorption mechanisms such as ion fundamental cyclotron absorption, second harmonic cyclotron absorption, mode conversion, electron Landau damping and transit-time magnetic pumping are considered. The electron absorption, which is the main source for the current drive by momentum transfer, is written in a form independent of the coordinate system and discussed in detail. Published expressions for the current drive efficiency and bootstrap current are then used for the current drive calculations. Neoclassical effects of electron trapping in the toroidal magnetic field of a tokamak and untrapping due to collisions are incorporated. Some considerations of current drive in Phaedrus-T by ICRF helicity waves are presented. The possible regimes of Phaedrus-T operation are discussed.

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Energy-Confinement-Timescale Numerical Tokamaks

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Over the past year there has been considerable discussion about the feasibility of a "numerical tokamak", a simulation of an entire tokamak based on near-first-principles physics and the future availability of teraFLOP computers. The "near-first-principles physics" stipulation implies that the numerical tokamak will involve three-dimensional simulations of fluctuation-timescale phenomena with minimal assumptions. As a paradigm for such a simulation we consider gyrokinetics and ion-temperature-gradient-driven turbulence, and estimate the running time on a teraFLOP computer required to simulate a large machine (BPX or ITER) for both turbulent and energy-cofinement timescales. Running times are estimated based on the number of particles required for adequate statistics, assuming that techniques such as semi-implicitness and electron orbit averaging lower noise and eliminate electron timestep constraints, and that, for the fluctuation-timescale estimates, only the perturbed distribution function is simulated (δf technique). Our conclusion is that simulation of even the entire tokamak for a fluctuation time is feasible ($\sim$ 10 min), while simulation for an energy confinement time is not ($\gtrsim 10^4$ hrs). Qualitatively similar conclusions have been drawn for fluid simulations[1]. But evolution of self-consistent profiles requires simulation on the energy-confinement timescale. Achievement of that objective will require integration of the results obtained from fluctuation simulations with reduced-dimensional descriptions. Examples of candidate descriptions are fluid codes averaged over the fluctuation timescale and over toroidal angle or the flux surface, flux-surface-averaged Fokker-Planck codes, and empirical spectral models[2]. We discuss possible modes of interaction between the reduced-dimensional and fluctuation-timescale simulations and survey the other ingredients required to produce a comprehensive energy-confinement-timescale simulation.

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ICRF-DRIVEN CONVECTIVE CELLS IN THE TOKAMAK EDGE PLASMA*

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Recently, we have shown that the release of metal impurities during ICRF heating on JET could be explained by ion acceleration into the Faraday screen (FS) surface caused by rf sheaths, which form when local magnetic field is imperfectly aligned with the FS. The theory explained many of the dependences of the impurity data, including the virtual elimination of impurities with beryllium screens and dipole antenna phasing. The good agreement between the impurity generation model and experimental data can be taken as evidence of the relevance of rf sheaths to the scrape-off-layer (SOL) plasma in tokamaks. A crucial physical point in sheath theory is that the requirement of no time-averaged current into the boundary leads to the "rectification" of the oscillating rf fields to produce a net time-averaged and spatially-varying potential and, hence, a DC electric field.

Here, we investigate the possibility that the rectified sheath potential Φ_0 can drive convective cells in the SOL which may explain the experimental observations of ICRF-enhanced edge transport on many tokamaks. Temperature (and sometimes density) profile flattening and induced DC electric fields in the SOL are often observed during ICRF heating on JET, particularly in monopole phasing. The attainment of the H-mode with ICRF heating alone is also sensitive to the phasing of the antenna. These observations suggest an rf-sheath related effect, as the magnitude of Φ_0 is much larger in monopole phasing (~ 1 kV near the FS). We speculate that enhanced edge cooling by rapid convection may account for the phasing sensitivity of the H-mode transition.

In the present work, a modified convective cell equation for the SOL plasma is derived, which explicitly takes into account the finite length of the field lines and the appropriate sheath boundary condition for $J_{||}$. This equation evolves the field-line averaged potential $\Phi(x,y)$ driven by Φ_0 and contains the usual equation for 2D incompressible Euler flow as a special case. An approximate penetration length L_x is estimated from this equation and various special cases will be solved. Progress in solving the general equation including many-mode coupling will be reported.

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PHYSICS BASIS FOR COMPACT IGNITION EXPERIMENTS*

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Compact toroidal ignition experiments with tight aspect ratios can be designed to attain peak densities $n_o \simeq 10^{15}$ cm^{-3} reliably and to achieve "low temperature" D-T ignition under conditions where the fusion heating due to α-particles does not exceed twice the ohmic heating power [1]. An average current density about 1 kA/cm^2 with a maximum plasma current $I_p = 12$ MA are the reference design parameters of the Ignitor Ult machine [2]. The peak density is consistent with the ratio of B/R_o, $R_o \simeq 1.3$ m and $B_T \simeq 13\ T$ in vacuum, when compared to the values of n_o obtained in the Alcator, FT, and TFTR machines. The vacuum toroidal field is enhanced by the large paramagnetic poloidal current, $I_\theta \lesssim 10$ MA. The high values of the poloidal field $B_p \simeq 3.9$ T produce a strong rate of ohmic heating, while the corresponding high values of I_p ensure that the fusion α-particles deposit their energy in the central part of the plasma column. A confinement parameter $n_o\tau_E \simeq 4 \times 10^{14}$ sec/cm^3 can then be expected to be achieved with considerable margin, taking into account that the high value of I_p also limits the degradation of the energy confinement time in the so-called L-regime, that is observed in present day experiments when injected heating prevails over ohmic heating. The necessary degree of plasma purity ($Z_{eff} \lesssim 1.6$) is expected to be ensured by the high particle densities and the high magnetic fields. When the effects of the initial current rise are considered [2], numerical simulations have shown that the ohmic power can remain considerable up to ignition and the volume of the plasma, where the magnetic parameter $q \leq 1$ and macroscopic $m^o = 1$ plasma modes may be excited, can be maintained relatively small [3]. The stability margin against these modes is made favorable by the uniquely low values of β-poloidal that are characteristic of Ignitor. An additional heating source of 15 MW of ICRF power is also planned, to broaden the scenarios under which ignition is achieved.

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Nonlinear Gyrofluid Equations for 3D Simulations of ITG Turbulence in a Sheared Slab

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We have developed gyrofluid equations for electrostatic microturbulence in sheared slab geometry, and have implemented them in a 3-D nonlinear fluid code[1]. Unlike most previous fluid equations, these gyrofluid equations include effective models of important kinetic and FLR effects which have been shown by recent gyrokinetic calculations[2] to reduce the transport by an order of magnitude.

Our recent work has focussed on deriving the gyrofluid equations by taking moments of the gyrokinetic equation in guiding-center coordinates rather than laboratory coordinates. This picks up nonlinear FLR terms and an important shear effect pointed out by Linsker[3] in a more natural way. The resulting gyrofluid equations describe the evolution of the guiding center n, $u_{||}$, $p_{||}$, and $p_{\perp}$, including an extension of our recently developed fluid model of Landau damping[4] to model the phase mixing of $p_{\perp}$ as well as $p_{||}$. This model provides a fairly good description of kinetic effects and is equivalent to an n-pole (n=3 in our case) approximation of the plasma dispersion function Z. The finite-gyro-radius effects in the Bessel functions are modelled in the code either by using Padé approximations or fast Fourier transforms. These have the advantage of being fairly accurate up to $k_{\perp}\rho \approx 1.5 - 2.0$ while not diverging at large $k_{\perp}\rho$ as Taylor-series do.

Although our work to date has focussed on electrostatic fluctuations in slab geometry, generalization to toroidal geometry seems feasible. An extension to bounce-averaged trapped electrons is carried out elsewhere in this conference[5]. Brizzard[6] has derived a set of gyrofluid equations for electromagnetic fluctuations in general toroidal geometry. His equations could be improved in several ways; for example, by adding a Landau damping model. Other developmental issues include the number of moment equations needed for sufficient accuracy, and the incorporation of collisional effects (along the lines of the recent work of Chang and Callen).

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Field Reversed Configuration (FRC) Equilibrium and Tilt Stability Modification by Energetic Beams.*

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Recent simulations indicate that energetic ions beams can stabilize the tilt mode in FRC's[1]. Further refinement has shown that beam deposition profiles for experimentally realizable neutral beam gun parameters are significantly different from initial idealized beam populations[2]. Here we analyze the modification of FRC equilibria and tilt stability by realistic energetic beams. Starting from an equilibrium without beams, evolution is followed numerically past beam injection using the modified FLX simulation algorithm with ray-tracing Monte-Carlo beam ionization calculations. First a calculation of n=0 equilibrium modifications is carried out under an axisymmetric (2-D) assumption. These modifications are compared with a 1-D FRC equilibrium transport calculation which includes beam effects. Finally, the axisymmetry assumption is relaxed in order to investigate the effect on the tilt instability. Additional diagnostics have been developed which allow instantaneous distribution function determination as a function of many different variables, even in low field regions where small larmour radius expansions fail.

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Nonlinear Gyroviscous Force and Its Effect on Momentum Balance Equations*

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The perturbed, nonlinear gyroviscous stress force ($\nabla \cdot \tilde{\Pi}_g$) up to order $\delta^{3/2}$ ($\delta \sim \omega/\Omega$, $k_\perp \rho \sim \delta^{1/2}$) is calculated by solving the stress tensor ($\tilde{\Pi}_g$) evolution equation. Part of the nonlinear gyroviscous force derived thereafter is shown to cancel the diamagnetic convective term $nm\mathbf{V}_* \cdot \nabla_\perp \tilde{\mathbf{u}}$ (where $\mathbf{V}_*$ is the generalized total diamagnetic drift) in the momentum balance equation, as was hypothesized previously [1]. This cancellation is different from the usual widely used "gyroviscous cancellation" [2], in which the gyroviscous force cancels mostly with $nmd\mathbf{V}_d/dt$, where $\mathbf{V}_d$ is the diamagnetic drift velocity. When temperature variations are neglected, linearized versions of both forms yield the same perturbed momentum balance equation. However, it is shown that when nonlinear terms are retained, a nonlinear term $\tilde{\mathbf{V}}_* \cdot \nabla_\perp \tilde{\mathbf{u}}_\perp$ was missing in the previous formula. In addition, when temperature variations are included the parallel compressibility terms no longer cancel in the previous formula. The polarization drift derived from the new formula exhibits a much simpler form than the usual one. The effect of the new gyroviscous cancellation on nonlinear plasma equations (*e.g.*, Hasegawa-Wakatani equations [3]) will be discussed.

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Comparison between numerical computations of island size with the BETAS code and other solutions*

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A variational approach to computation of island size in finite pressure 3D equilibrium configurations has been previously presented[1,2]. The method is very efficient and can be applied to the study of island formation in Tokamaks and Stellarators. The results can also be used as a basis for Monte Carlo calculations of the effect of bifurcated equilibria and island formation on transport properties.

We test the accuracy of this method by comparing our results with analitical solutions or numerical results obtained by other authors.

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1D17

Computational Study of Inertial Range Spectral Transfer by E×B and Polarization Drift Nonlinearities

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Spectral transfer processes in drift wave turbulence models, including fluid models for trapped particle modes, are governed by two nonlinearities, the polarization drift nonlinearity $n_0\nabla\cdot\mathbf{v}_p^{(1)}$ which dominates at short scale ($k_\theta\rho_s \gtrsim 1$), and the E×B nonlinearity $\mathbf{v}_E\cdot\nabla\,\tilde{n}$ which dominates at large scale. Here, $\mathbf{v}_p^{(1)} = B_0^{-1}(c/q)\mathbf{b}\times\mathbf{v}_E\cdot\nabla\mathbf{v}_E$ is the nonlinear polarization drift, $\mathbf{v}_E$ is the E×B drift, and $\tilde{n}$ is the fluctuating density. The polarization drift nonlinearity admits two quadratic invariants (typically energy and enstrophy or mean square vorticity). This gives rise to a dual cascade process analogous to the cascade of 2-D Navier Stokes turbulence, in which enstrophy is cascaded to small scale and energy to large scale. The E×B nonlinearity is typically dominated by the dissipative contribution of nonadiabatic electrons to the density fluctuations and conserves only energy, which is cascaded to small scale. In addition, the E×B nonlinearity is capable of energy transfer which is strongly nonlocal in wavenumber space. In the past, drift wave turbulence models have generally considered one nonlinearity or the other, but not both.

In this work we report on initial results of a numerical study of the interplay of turbulent transfer by these two nonlinearities within a single drift wave model. From spectral and pseudospectral simulations, turbulent transfer properties in various parts of the spectrum, as well as the net transfer characteristics, are inferred from equilibrium spectra. Direct measurement of local and nonlocal inertial transfer into or out of selected regions of wavenumber space is accomplished and compared with the equilibrium spectrum and theoretical results (adjacent poster). These measurements are made for undriven, undamped inertial flow from initial spectra which are consistent with similarity transfer from stirred large scales to dissipated small scales and theoretical spectra for toroidicity induced trapped electron mode turbulence.

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Nonlinear Interaction of Radial Eigenmodes In ITG Turbulence

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Analytical and numerical calculations indicate there exists a spectrum of unstable radial ion temperature gradient driven (η_i) modes. Also studies reveal that background electric fields provide a mechanism for coupling among different radial modes[1]. However, such "radial" nonlinear interaction has not been properly treated, leading to deficiencies in past work. For example, in the conventional approach of treating the renormalized turbulent diffusivities as the eigenvalues of the nonlinear eigenmode equation[2], there emerges the dubious artifact of turbulent diffusivities corresponding to different radial eigenmodes. By treating radial modes at different helicities as a "turbulent background", and considering the interaction of different radial modes on the same rational surface[3], we calculate the necessary l-mode coupling spectral flow in l space, allowing saturation of **all** radial modes. The satuation level is then calculated, and compared with the mixing length theory estimates.

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Dynamics of Toroidal Electron Drift Wave Turbulence

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We discuss several novel developments in the theory of dissipative and collisionless electron drift wave turbulence. Our emphasis is on spectral transfer mechanisms, nonlocal interactions, and the structure of fluctuation spectra.

In the case of the dissipative trapped electron regime, a density equation with two quadratic nonlinearities is derived. The two nonlinearities, $\mathbf{E} \times \mathbf{B}_0$ and polarization, transfer spectral energy in opposite directions. In particular, the $\mathbf{E} \times \mathbf{B}_0$ nonlinearity acts to cut-off the well-knwon inverse cascade to large scales, and establishes a direct cascade range for $k_\theta \rho < k_0 \rho = \sqrt{\varepsilon}\; C_s/L_{Te}\, \nu_{ee}$. As a result, the spectral shape is different for $k_\theta \rho \gtrless k_0 \rho$. Also, the long wavelength dynamics are noted to be similar to that of trapped ion modes, thus smoothly joining shorter wavelength drift wave turbulence to them. Ion Compton scattering is shown to be irrelevant for toroidal modes, due to the flute-like nature of their structure. Spectra, fluctuation levels and transport coefficients are calculated.

In the collisionless regime, trapped electron mode coupling has been established to be an important effect, and more robust than trapped electron Compton scattering, which is highly sensitive to resonance conditions. An electron mode coupling equation has been derived. An assessment of the competition between electron and ion nonlinear processes is underway and will be discussed.

Finally, we investigate nonlocal interaction processes in drift wave turbulence. In particular, modulational interactions and parametric subharmonic instabilities are addressed. Some speculations on the relation between long wavelength drift wave turbulence and non-local transport processes are discussed in light of the modulational interaction.

TRAPPED ION TURBULENCE IN TOKAMAKS

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It is usually admitted that ion turbulence contributes in some cases to ion anomalous heat transport, especially when the ion temperature gradient is large. The question of calculating accurately the thresholds for such a turbulence then arises. This determination has been achieved by using the code TORRID [1] which calculates marginal thresholds and associated linear eigenmodes. This kinetic code takes account of circulating and trapped particle resonances and calculates modes within the frame of the ballooning approximation. It appears that the most dangerous instabilities are driven by trapped ions, with a corresponding threshold given by $(1+T_i/T_e)\ L_{Ti}/R = 0.2 \div 0.3$. It seems that most of experimental ion temperature profiles do not exceed this threshold.

The latter result corresponds to the zeroth order of the ballooning formalism, i.e., an infinite series of identical Fourier modes localized near their corresponding resonant surfaces. A study of the next order allows the calculation of an envelope and it will be shown that its radial scale is a geometric mean of a gradient scale (the smallest of density, temperature and plasma velocity gradient scales) and a thermal banana width. A simple mixing length estimate of the ion thermal diffusivity gives therefore a large value of the ion heat flux once the L_{Ti}/R threshold is exceeded. However, a quasilinear study shows that such a turbulence can induce a differential rotation of the plasma, which is then able to stabilize the largest scale instabilities. The resulting turbulence should therefore exhibit smaller scales than expected. Nevertheless, the heat ion transport remains large.

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1991 SHERWOOD INTERNATIONAL FUSION THEORY CONFERENCE

The Second Criterion For A Thermonuclear Reactor And Some Possible Ways To Lower It

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The Lawson Criterion(the First Criterion) only considers bremsstrahlung loss from a plasma and neglects all other energy losses from the whole fusion reactor, that makes it much lower than that required of an actual fusion reactor. Thus an important parameter η_H — the overall heating efficiency of the fusion reactor must be added to the criterion. It is defined as $\eta_H = (3nKT + P_b\tau)V/W_f$,where W_f is the total energy of reactor consumption per pulsed period; n, τ, T and V are the density,confinement time,temperature and volume of its plasma,respectively; P_b is the bremsstrahlung power. Only a fraction of W_f is injected into its plasma, namely W_p , and only a fraction of W_p is valid,which is equal to $(3nKT + P_b\tau)V$. The rest of W_p are invalid, which are dissipated in heat conduct,cyclotron radiation,particle escape, etc. If the fraction of the nuclear reaction energy retained as thermal energy in the plasma is C,and the efficiency of energy conversion is η. Then the energy gain and breakeven conditions for a fusion reactor is

$$\eta[3nKT + P_b\tau + (1-C)P_r\tau] \geqslant (3nKT + P_b\tau - CP_r\tau)/\eta_H \qquad (1)$$

where P_r is the nuclear power released in a plasma per unit volume. Thus a space of three dimensions can be composed of plasma temperature T, the product of density n and confinement time τ, and η_H from the eq.(1). The breakeven conditions for the actual fusion reactor are given by a surface in this space. It is called the Second Criterion for realizing the breakeven. The values of main fusion parameters under breakeven conditions and the relations between them can be completely shown by the Second Criterion[1]. They are in agreement with those values required for the actual fusion reactor. The Lawson Criterion expressed in the $n\tau$- T space of two dimensions is a special example of the Second Criterion. The aim of investigating the fusion reactor criterion is to explore and to search for some ways to lower it. Some possible ways to lower this criterion are presented in this paper. So far a few ways have been presented, such as a new quantum effect in nuclear fusion[2], a new mechanism of thermonuclear reaction[3], etc.

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Effects of Interacting Magnetic Islands on Magnetic Topology and Plasma Transport

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Density and temperature gradients via neoclassical effects can cause the growth of magnetic islands in the nonlinear Rutherford regime of tearing mode theory.[1,2] As neighboring magnetic islands interact, profiles of the plasma density and temperature in the vicinity of the island separatrix flatten; thus, the free energy source for the magnetic perturbation is shut off. In addition, the diamagnetic flow velocity tends toward zero and thus drift wave effects are reduced. A model is presented that takes both the neoclassical pressure gradient effect and island interaction into account. The magnetic configuration is described as a bath of low to medium mode number ($m \cong 3$–10) magnetic islands whose amplitudes sporadically grow and decay (*"magnetic bubbling"*). The effects of magnetic islands produced by low to medium mode number magnetic perturbations are generally not addressed in statistical theories of transport due to magnetic turbulence, where coherent structures are mostly neglected and magnetic stochasticity is usually assumed because of island overlap.[3] Consequently, the transport due to magnetic bubbling has a different character than that described by stochastic processes since the magnetic island width becomes the cross-field step size for plasma transport.[4] These studies suggest the possibility that tokamak discharges have short-lived (approximately 1 msec) relatively coherent magnetic structures present.

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Effects of the electron temperature gradient on the instability due to the ion temperature gradient*

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Effects of the electron temperature gradient (η_e) are included in the study of the instability and the resulting transport of the energy due to the ion temperature gradient (η_i). The instability occurs in the spatial scale of the ion gyro-radius and is suggested to be responsible for the energy transport in the experiments. In most previous works, the electrons are assumed to be adiabatic. Thereby, the electron temperature fluctuation is absent from the analysis. However, in experiments, the electron temperature is fluctuating and the gradient of the mean electron temperature is comparable to that of the ion temperature. In this work, two-component fluid descriptions are employed for both the ions and the electrons in the slab geometry. The critical value η_{ic} for the linear instability depends strongly on the value η_e. Thus, η_{ic} is different from the critical value η'_{ic} computed in the previous works, where $\eta'_{ic} \approx 2/3$. For the study of the transport of the energy due to the instability, numerical simulation is done. Detailed results will be presented and discussed.

* Work supported by U.S.D.o.E. Contract No. DE–FG05–80ET53088.

3-D MHD SIMULATIONS OF RFPs INCLUDING SELF-CONSISTENT TRANSPORT

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New semi-implicit operators have been derived to handle anisotropic thermal conduction. These operators allow for strong thermal conduction parallel to the magnetic field with a minimal amount of cross-field poisoning. These operators will be discussed and numerical tests will be presented.

These new algorithms have been applied to finite presssure RFP calculations to study self-consistent transport induced by tearing modes and pressure-driven modes. Results indicate that the RFP forms a turbulent core surrounded by a confining region, as has been suggested by previous zero pressure studies[1]. The pressure profile flattens in the turbulent regions and the pressure gradients are supported by the comparitively benign edge region. The plasma beta values observed are in reasonable agreement with experimental data. Experimentally observed sawtooth oscillations have also been seen with the simulations.

The addition of the finite pressure results in a spreading of the spectrum to shorter wavelengths. The dominant pressure-driven modes have the same parity as the tearing modes observed in the zero pressure simulations, but with much reduced growth rates. Results are very sensitive to the amount of viscosity present in the simulations. Examples will be presented.

1. D. D. Schnack, E. J. Caramana, and R. A. Nebel, Phys. Fluids **28**, 321 (1985).

Empirical Orthogonal Functions for ITG Turbulence Simulation*

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Empirical orthogonal functions (EOF's; the eigenfunctions of an autocorrelation matrix) provide a means of capturing the essential information about a complicated field with a minimum number of basis functions. We have constructed a code to generate EOF's from fluid simulations of electrostatic turbulence. We present results from an application to simulations of ion-temperature-gradient turbulence in a two-dimensional shearless[1] and sheared [1] slab. The shearless simulations are distinguished by the presence of elongated coherent structures ("streamers"). We explore the number of EOF's required to recover the streamer structure and other salient features of the simulations. This work is part of a larger effort to use EOF's as an efficient basis set for simulations ("empirical spectral models", or ESM's) of tokamak turbulence. We describe prospects for using ESM's as a means to bridge the gap between the fluctuation and energy-confinement time scales in a numerical tokamak. Finally, we describe an extension of the EOF formalism to phase space which enables an empirical spectral model based on gyrokinetics.

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

[1] T. Antonsen *et al.*, in *Plasma Physics and Controlled Nuclear Fusion Research 1988*, Nice, France (IAEA, Vienna, 1989), Vol. II, p. 251

[1] A. M. Dimits, J. F. Drake, P. N. Guzdar, and A. B. Hassam, to be published in Phys. Fluids

1991 SHERWOOD THEORY CONFERENCE
SEATTLE, WASHINGTON

ON RESONANT EXCITATION OF HIGH-n MAGNETOHYDRODYNAMIC MODES BY ENERGETIC IONS/ALPHA PARTICLES IN TOKAMAKS

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Experimental observations of MHD fluctuations during auxiliary ICRF/NB heating on tokamaks have spurred considerable theoretical activity on the stability characteristics of MHD modes in the presence of energetic particles. A related concern pertains to the influence of energetic alpha particles on such modes in ignited plasma regimes. Here, we present an analytic theory which considers the resonant excitation of high-n MHD instabilities by energetic ions/alpha particles. Employing the ballooning formalism and a two-spatial scale expansion, we derive a unified dispersion relation which retains four different types of resonant interactions:

(P) trapped-ion precessional drift resonances ($\omega \simeq \bar{\omega}_{dh}$),
(T) circulating-ion transit resonances ($\omega \simeq \omega_{th}$),
(B) trapped-ion magnetic bounce resonances ($\omega \simeq \omega_{bh}$),
(PB) trapped-ion hybrid magnetic precessional drift-bounce resonances ($\bar{\omega}_{dh} \simeq \omega_{bh}$).

The first of these can be triggered away from the Troyon ideal ballooning stability boundary, but requires a finite population of energetic ions in order to overcome the strong stabilizing influence associated with continuum damping. The latter three instabilities, however, are predominantly thresholdless, but are triggered only as one approches the ideal ballooning stability boundary where the MHD modes become discrete ($\omega = \omega_{*pi}$). This is related to the fact that P-type resonances contribute to the ideal region, while the other types of resonances influence inertial layer dynamics. General considerations show that the more energetic the class of ions that are tapped in the resonant interaction, the more virulent the nature of the excitation. Thus, PB resonances are shown to be the most serious type of interaction for trapped ions from the stability point of view, and a more plausible candidate to explain the high-n precursor oscillations to fishbones as observed on PDX than P-type resonances. Detailed expressions for the growth rates and wavelength characteristics of each type of interaction will be given, and implications for DIII-D, TFTR ,BPX, and JET will be discussed.

GUIDING CENTER DIFFUSION INDUCED BY STOCHASTIC ∇B- AND CURVATURE DRIFTS

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The transport of guiding centers due to stochastic magnetic field fluctuations is analyzed, and special attention is paid on the effect of ∇B- and curvature drifts. We consider a uniform magnetic field with small stochastic fluctuations that exhibit both time and space dependence. Starting from the standard guiding center equations with $V_{||}$ = constant, and using some techniques from the theory of stochastic differential equations and the Novikov's theorem, we derive an equation for the probability density function, which yields the probability of finding a guiding center around a given point in the configuration space, at a given time. Using this equation we find equations for the mean square displacement of the guiding centers, from where an expression for the diffusion coefficient is found. Assuming stationary axisymmetric turbulence, we express this coefficient in terms of four functions that characterize the magnetic fluctuations. With the condition that these fluctuations are divergence-free, the number of these functions reduce to only two. By proposing analytical forms for these functions we evaluate the diffusion due to stochastic ∇B- and curvature drifts, and compare it to the transport induced by an stochastic weak breaking of magnetic surfaces.

1D28

Edge Turbulent Transport Critical Comparisons*

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A critical comparison between edge turbulent transport theoretical calculations and experimental measurements will be given. Particular emphasis will be given to recent results on field correlation analyses which include density, potential, and temperature fluctuations $(\tilde{n}-\tilde{\phi}, \tilde{n}-\tilde{T}, \tilde{\phi}-\tilde{T})$. The theoretical framework consists of a set of resistive MHD equations for the drift-rippling[1] theory which is used to evolve the density, potential, velocity, and temperature fluctuations. The experimental comparisons will be made against data bases from TEXT (UTA) and CCT (UCLA) observations. It is shown that the field correlation information leads to a new level of theoretical understanding of the turbulent edge.

[1]D. R. Thayer and P. H. Diamond, Phys. Rev. Lett. 65, 2784 (1990).
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[1]H. Lin, R. D. Bengston, and Ch. P. Ritz, Bull. Am. Phys. Soc. 34, 2154 (1989).
*Work supported by the U. S. Department of Energy.

Electric Field Inhomogeneities and Ion Temperature Gradient Modes in a Sheared Slab

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The effects of spatially inhomogeneous equilibrium electric fields on a fully-kinetic model of the ion temperature gradient (ITG) mode in a sheared slab magnetic field is investigated. The electric field structure in the region a few centimeters inside the magnetic separatrix of a DIII–D plasma exhibits a well which is deepened during the transition to H–mode [1]. Both first and second derivatives of the electric field are needed in order to model the electric well structure throughout the region of suppressed fluctuations. It is found that a gradient of the electric field of either sign, or a positive second derivative, reduces both the growth rate and the transport rates for heat and particles. The combined effect of a deepened electric well is found to be strongly stabilizing for ITG modes in the experimental range of parameters for H–mode. The stabilizing effect is primarily attributed to changes in the Landau damping by the ion kinetic response function. The kinetic electron response has a slightly destabilizing influence for small electric field gradients. These slab model calculations demonstrate that inhomogeneous electric fields can reduce the growth rates obtained from linear stability theory for ITG modes, and add support to the conjecture that electric field changes at the L/H transition suppress turbulent transport in a narrow zone near the plasma edge. The mechanism of turbulence suppression is at the level of linear stability rather than the saturated turbulence decorrelation of Biglari, Diamond, and Terry [2].

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

[1] R.J. Groebner, W.A. Peebles, K.H. Burrell, *et al.*, in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 13th Int. Conf. Washington, 1990), IAEA, Vienna, to be published.

[2] H. Biglari, P.H. Diamond, and P.W. Terry, Phys. Fluids B **2** (1990) 1.

1991 Sherwood Conference

Gyrokinetic Particle Simulation of Impurity Transport*

by
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The effects of ion temperature gradient drift instabilities on the particle transport of the plasma impurities have been investigated using both 2D and 3D gyrokinetic particle simulation codes in slab geometry. To account for the various impurity concentrations and atomic numbers (Z), we have also used a newly derived gyrokinetic Poisson's equation in the simulation. The cases under consideration are those with and without shear as well as those with and without electron-ion collisions. It is found that the inward impurity particle flux is consisted of two components --1) an inward pinch and 2) an inward diffusion. This inward particle flux has been observed to occur in the linear stage of the instability and to persist long after the nonlinear saturation at a level comparable to but somewhat lower than the quaslinear value. Moreover, ambipolarity condition requires an enhanced level of the outward particle flux for the primary ions, which has also been observed. Finally, the finite-ß effects on the impurity transport will also be reported.

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1D31

1991 Sherwood Conference

Gyrokinetic Particle Simulation of Finite-ß Modified Ion Temperature Gradient Drift Instabilities*

by

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A linearized gyrokinetic particle simulation of finite-ß modified ion temperature gradient drift instablities (η_i modes) is presented and compared with the results from a linear integral eigenmode code. In the electrostatic limit, an extra term in the resonant denominator due to the finite Larmor radius effects[1] has been shown to play an important role in determining the mode structures for the modes with $k_\perp \rho_i \sim O(1)$. This term is automatically included in the gyrokinetic simulation model,[2] but not in the usual linear eigenmode equations. The effects of this Linsker's term in the finite-ß limit are the focus of the present investigation. The nonlinear evolution of the finite-ß modified η_i modes will also be discussed.

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* This work is supported by the DoE contract No. DE-AC02-76-CHO-3073.

1 R. Linsker, Phys. Fluids **24**, 1485 (1981).

2 W. W. Lee, J. Comput. Phys. **72**, 243 (1987).

A New Look at Time Dependent Transport of Magnetic Helicity*

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This paper has two purposes. First, a new definition of magnetic helicity is presented to give a sharper distinction between inductive and parallel-electrostatic magnetic helicity transport. Second, a theorem is described which states that only parallel-electrostatic transport can indefinitely sustain magnetic helicity dissipation in a torus, where the boundary moves to maintain a constant volume averaged toroidal flux.

The concept of magnetic helicity lends considerable simplification to the descriptions of plasma relaxation,[1] current drive,[2] or Ohmic dissipation.[3] The definition of magnetic helicity, $K \equiv \int \mathbf{A}\cdot\mathbf{B}\,dV$, used in Refs. 2 and 3 is only applicable to closed volumes where no magnetic field penetrates the surface. In a torus, gauge invariance is maintained by subtracting, from $\mathbf{A}$, the contribution due to transformer flux through the core of the torus. When magnetic field penetrates the surface under consideration, K can be made gauge invariant by subtracting a vacuum field term,[4,5] $\mathbf{A}_P\cdot\mathbf{P}$.

For the present theorem, if the volume under consideration is toroidal its surface must be allowed to move radially to keep the volume averaged toroidal flux constant in time. Such moving boundaries can always be located inside a tokamak or a Reversed Field Pinch. In the sense of Refs. 2 and 3, the surface averaged transformer contribution to $\mathbf{A}$ is subtracted. The gauge of $\mathbf{A}$ is chosen such that $\nabla_S\cdot\mathbf{A} = 0$ on the surface of integration, where ∇_S is defined only to operate in the two coordinates tangent to the surface. The electric field $\mathbf{E} = -\nabla\phi - \partial\mathbf{A}/\partial t$ is now divided into explicitly electrostatic, ϕ, and inductive, $\mathbf{A}$, components. If the macroscopic nature of $\mathbf{B}$ and the linked transformer flux do not change over a "long" period of time, then $\int \mathbf{E}\cdot\mathbf{B}\,dV = \int \eta\mathbf{J}\cdot\mathbf{B}\,dV = -\int \phi\mathbf{B}\cdot d\mathbf{s}$ when averaged over time. This result is well known for time independent fields,[4] and now it clearly extends to time varying fields that undergo no macroscopic change over an extended period. If magnetic helicity dissipation is an essential part of plasma sustainment, there is no inductive mechanism that can transport magnetic helicity into a volume without connecting field lines across the surface of that volume.

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* Work performed under the auspices of the USDOE.

[1] J. B. Taylor, *Phys. Rev. Lett.* **33**, 139 (1974).

[2] M. K. Bevir and J. W. Gray, in *Proc. of the Reversed-Field Pinch Theory Workshop*, Los Alamos 1981, Report No. LA-8944-C.

[3] K. F. Schoenberg, R. W. Moses, and R. L. Hagenson, *Phys. Fluids* **27**, 1671 (1984).

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[5] D. C. Barnes, *Phys. Fluids* **31**, 2214 (1988).

Control Theoretic Techniques Applied to Tokamak Controls

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We are developing theoretical methods for determining the robustness of the poloidal field control system [1].

Here we introduce a restricted condition number based on a subset of the singular values of the inductance matrix. For example, if it is determined that eight control parameters are necessary in order to generate and maintain a desired plasma shape, then the restricted condition number, $\mathcal{C}_n$, is the ratio of the first to eighth singular values. This is a correct condition number when the inversion of the inductance matrix is approximated by its first eight singular values. Such an inversion preserves significant information, but filters out undesired sensitivity to errors and noise.

When only a limited number of singular values are kept, the poloidal positioning of the sensor loops can be important. Here this positioning is varied with the object of finding the optimal positions. The positions found this way are optimal for transferring information from the loops to the poloidal field forming coils, but not for determining the plasma shape and position. The overall optimum will be determined by a compromise between these conditions.

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

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Study of Alfvén Wave Instabilities Using a Hybrid Particle-Fluid Code

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In the presence of magnetic field inhomogeneity and energetic particles, Alfvén waves can be unstable through wave particle resonances [1-3]. Here we present a study of Alfvén-type instabilities driven by fusion products of energetic alpha particles using a hybrid particle-fluid code. In the study, we consider a plasma consisting of two coponents: a background plasma of ions and electrons, and an energetic species of alpha particles. The ideal MHD description is adopted for the background plasma, the evolution of which is determined by a set of fluid equations for vorticity $\nabla_\perp^2 \phi$ and parallel components of the vector potential $A_\parallel$. For the energetic species of alphas particles, we adopt a guiding center formalism to describe the particle motion in the electromagnetic field, which allows for full account of wave particle resonances. The code can simulate either single mode or multiple mode dynamics, and is fully nonlinear in the sense that both $\vec{E} \times \vec{B}$ convective and magnetic "fluttering" nonlinearities are included, thus capable of simulating Alfvén turbulence and the resulting anomalous alpha transport as well. Current investigations in the slab geometry concentrate on the physics issues of linear instabilities and nonlinear evolution of the modes. The results of this investigation will be presented.

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Stabilizing Tokamak Microturbulence by Driven Poloidal Rotation

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Recent experimental evidence and theory indicate that sheared poloidal rotation of tokamaks can quell microturbulence. It is suggested that poloidal rotation with sufficiently large shear can be driven in the bulk tokamak plasma with existing neutral beam power in an attempt to improve confinement *in the core plasma.*

The linear theory of three representative tokamak microinstabilities, the resistive-g mode[1] , the η_i mode[2], and the drift wave, is examined. In all cases, it is shown that sufficiently large poloidal velocity shear can stabilize these modes. Other authors have concluded similarly[1,2]. In all cases, the critical velocity shear V_θ' needed for stabilization can be characterized in order of magnitude by

$$V_\theta' > c_s/R \tag{1}$$

where R is the major radius and c_s is the sound speed.

The possibility of driving poloidal rotation in the core plasma by neutral beams injected perpendicularly off-axis is examined. From momentum conservation, the maximum poloidal speed attained for a beam heated plasma is found to be given by the formula

$$V_\theta/c_s \simeq (1/2)(a/\Delta a)^{1/2}[10/\tau_E(ms)] \propto T^2/n \tag{2}$$

where Δa is the radial scale of beam collimation, a is the minor radius, and τ_E is the energy confinement time in ms. The assumptions have been made that $T = 10keV$ and $n = 10^{14}cm^{-3}$, that the magnetic pumping rate is of order ν_{ii}, and that the average beam injection energy is 80 keV. Condition (1) may be attainable for modestly small Δa and confinement times of order 100 ms.

Side effects of driving such large poloidal rotations, such as MHD equilibrium modification and the possibility of triggering Kelvin-Helmholtz instabilities, will be discussed.

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2. S. Hamaguchi and W. Horton, Bull. Am. Phys. Soc. **35**, 1982 (1990); X. -H. Wang and P. Diamond (to be published).

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Simulation and Modeling of Dissipative Drift Wave Turbulence*

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We present results of an extensive study of dissipative drift wave turbulence based on a two-field model with separate equations for plasma density $\hat{n}$ and potential $\hat{\phi}$.[1] The governing equations, which are a useful paradigm for conventional drift instabilities in certain parameter regimes ($\alpha > 1$), are also representative of other low frequency instabilities when $\alpha < 1$. Varying this adiabaticity parameter affects the coupling of the $\hat{n}$ and $\hat{\phi}$ fields and the role of the parallel dynamics. We present simulation results in the form of k-spectra, fluctuation levels, and color flow visualizations. Additionally, we use our direct interaction code for comparison and to test the validity of basic assumptions made in closure estimates.

A major result of the study is to point out the effect of the adiabaticity parameter on the formation of coherent structures and the resultant impact on transport. Contrasts between the cases where $\alpha \ll 1$ and $\alpha > 1$ are emphasized. In particular, for $\alpha > 1$, closely-packed (i.e. spatially non-intermittent) structures form in vorticity while density and potential are amorphous. However, for $\alpha \ll 1$, long-lived intermittent structures are observed in **both** the vorticity and density. Particle fluxes are used to provide transport estimates. Simulation code results of fluxes are compared with quasi-linear theory, mixing-length theory, and dimensional scaling estimates. For example, for $\alpha > 1.0$ there is good quantitative agreement between the simulation code and quasilinear theory predictions with the flux scaling roughly as α^{-1}. In the opposite limit, $\alpha \ll 1$, the flux obtained from the simulation code scales as $\alpha^{-1/3}$, in reasonable agreement with a dimension scaling estimate. Here, when structures appear in the density, quasilinear estimates are not accurate.

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* Performed by LLNL for USDoE under Contr. W-7405-ENG-48.

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Super Classical Heat and Particle Transport in Fusion Plasmas.

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It now appears that a slightly modified neoclassical theory can account for ion transport in toroidal devices, where the recently determined importance of radial E fields implies that ambipolarity is not intrinsic (coulomb collisional) but only automatic (toroidal). One consequence of this "anomalous" ambipolarity is that the small parallel neoclassical ion viscosity is not sufficient to account for large observed diffusivities. Nevertheless, the large perpendicular neoclassical ion viscosity is experimentally verified in plasmas with H-modes in CCT. These considerations leave electron perpendicular behavior still anomalous (100x neoclassical). (The electron parallel conductivity is not anomalous i.e., close to "neo" Spitzer.)

A series of investigations in CCT reveals that the plasma electrons behave classically on both the ion gyro and the collisionless skin depth scales. That is, their motion is determined by their thermal distribution (free-streaming), by initial conditions (perturbations), the self-consistent electromagnetic fields (Alfven waves), radiation forces (Alfven-Cherenkov) and relevant collisions. Specifically, it is found that microscopic density perturbations relax along the electron guiding center trajectories and that in the process bunched electrons radiate (relax) their field energy into "Alfven-Cherenkov" cones. These cones have a width of the order of the skin-depth for "heat perturbations" (Poynting flux) and of order of the ion gyro radius for density perturbations. Their longitudinal lengths are typically a "modified-Alfven" wavelength. Finite gyro radius effects, phase mixing, and ion-ion collisional damping play a major role, while resonant Landau damping is not effectual. Due to the long parallel relaxation lengths and the lack of "line tracking", the density and heat disturbances wander away from the magnetic surfaces at a projected fraction of the Alfven speed. The fraction depends on the existence of neighboring filaments and dc bias fields, and it can result in a large "scintillation disk" for the non-local, time-averaged, transverse correlation function. However, even in the absence of any mass transport, the electron heat transport is still governed by the "Aflven-Cherenkov filaments", where radiation is stimulated by parallel current relaxations driven by parallel density gradients. These fluctuations are not anomalous; they are relaxational and are absolutely stable due to the nonlinearities present in the microscopic relaxation physics. (Global MHD for a device may still be unstable!)

In conclusion, transport does not appear to be related to the lack of confinement of the field lines, nor to "collision less instabilities" and similar modes but it is related to fundamental radiation in gradient dominated plasmas - in fact, resulting in a super classical behavior. The neo-Alcator scaling is recovered theoretically, including the various forms of Goldston degradations (from 1982 to 1991) in the presence of auxiliary heating. The limiting forms of our results are close to earlier estimates by Ohkawa (before 1982) and Horton (before 1987) based on simpler collisionless skin-depth arguments. A low cost ignition device can be visualized from the results, where R (30 m) is large but a (1 m) and B (3 T) are small.

Special Session on New Directions
Monday, April 22, 1991, 8:00 - 10:00 p.m.

Chair: Akira Hasegawa

In view of recent cutbacks in the funding of fusion research, we need to respond positively by launching new initiatives in the direction of public concerns for the 1990s.

1. ***Non-Energy Applications of Fusion Research***
   Speaker: Prof. John Dawson, UCLA—There are many potential spin off applications of fusion power technology that have received relatively little attention. Fusion reactors produce their energy in unique forms; this energy could be used directly for many processes. Such applications can significantly alter the required conditions for economic fusion reactors. Fusion reactors produce much of their power as energetic particles. In the case of the D-^{3}He system large quantities of 15 Mev protons are produced. Such protons are ideal for producing proton rich nuclei through p-n reactions, which are used extensively in Medicine to produce positron emitting isotopes for PET-scans. There are potential applications of PET scans in industry if the cost of positron sources can be lower. Another use is to convert certain long lived neutron rich fission products to stable isotopes. Another application of fusion technology arises from using ion cyclotron energization of specific isotopes. The energized isotope can be separated from the bulk of the plasma by a variety of methods. (This isotope separation method is already in use to obtain substantial amount of ^{102}Pd which is being applied to treat prostate cancer.)

2. ***The Plasma Physics of Plasma Processing***
   Speaker: Prof. Leon Shohet, Director, Engineering Research Center for Plasma-Aided Manufacturing, U of Wisconsin—Plasma processing is used for producing new materials with unusual and superior properties, for developing new chemical compounds and processes, for machining, and for altering and refining materials and surfaces. It has direct applications to semiconductor fabrication, materials synthesis, welding, lighting, polymers, anti-corrosion coatings, machine tools, metallurgy, electrical and electronics devices, hazardous waste removal, high performance ceramics, and many other items in both high-technology and the more "traditional" industries. Plasma processing takes on a wide variety of apparently different forms in industry, but the techniques share many common characteristics and problems. Control of the generation and flux of ions, electrons and free radicals in the plasma and their incidence on a surface is vital. Diagnostics, sensors, modeling techniques, and associated statistical methods are needed. However, without an in-depth understanding of the variety of phenomena taking place and their application to the industrial environment, advances in this technology, and its efficient use, will occur at a diminishing rate.

Abstract for Invited Talk: Walter Gekelman
Sherwood Meeting

Title: Experiments on Collisionless Reconnection and the Interaction of Current Channels

A neutral magnetic sheet in which the current is carried mainly by the electrons is set up in a nearly collisionless (l_{mfp} = 2m=machine length, $R_m \approx 10$) laboratory plasma. When the current sheet is forced to be sufficiently narrow (length/thickness ≈ 30) the current is observed to tear. The tearing of the finite dimension current sheet (Lx = 40cm, Ly = 100cm, Lz = 1.3cm) is fully three dimensional. The 3D currents are evaluated from magnetic field ($\mathbf{j} = 1/\mu_0 \nabla \times B$) acquired at 5000 spatial positions and thousands oftime steps. Tearing is accompanied by the generation of significant Hall currents and, magnetic disturbances are observed to propagate at the whistler wave speed. In spite of its 3D nature the tearing mode growth time is in good agreement with linear 2D theory. In a series of related experiments the interaction of two current channels with appreciable self fields ($\mathbf{B}_{current} \approx 0.1\mathbf{B}_y$) are investigated in a newly constructed 10m long device. The current filaments are observed to merge while sprialing around each other. The system relaxes toward a force free state ($\mathbf{j} \parallel \mathbf{B}$) and helicity is conserved in the process.

LANDAU FLUID EQUATIONS FOR FINITE BETA THREE SPECIES ALFVEN WAVES*

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The nonlinear saturation of various toroidal Alfvén modes is of considerable interest and can be studied in a fluid context provided one can include Landau damping. Previously, we showed how to include Landau damping in the fluid equations for electrostatic modes by using an appropriate closure relation. Here we extend this work to include finite beta effects (i.e., non-zero $A_{\|}$ and $B_{\|}$). The macroscopic equations are developed from the gyro-kinetic equation in a form that allows direct comparison with the fluid equations used in the absence of Landau damping (e.g. vorticity evolution equation). By studying the local dispersion relation for Alfvén waves in slab geometry, we are able to determine the linear effect of omitting various phenomena (e.g., electron Landau damping) and thus partially justify using fewer non-linear evolution equations. This also allows us to compare a hierarchy of fluid evolution-closure equations to the full kinetic solution – again partially justifying the use of fewer non-linear evolution equations.

The key to including Landau damping in the fluid equations is to express the Fourier components of the nth moment of $v_{\|}$ as a linear combination of the lower moments and the electrostatic potential. Determining the coefficients in this relation corresponds to approximating the plasma dispersion function by a ratio of polynomials, the so-called n-pole approximations. We compare the original kinetic approach of Fried, McCune, and Hedrick for determining the one and two pole approximations with the present approach. We also show how the present approach leads to electrostatic results obtained by Hammett and Perkins, and by Callen et al., and why a rapid way of obtaining the electrostatic results fails when non-zero $A_{\|}$ and/or $B_{\|}$ are included. We compare the solutions to various dispersion relations for a variety of n-pole approximations with the exact kinetic results. We have considered resistive g-modes, ion temperature gradient modes, ionization driven drift waves, whistlers, and shear Alfvén modes with alpha particles present. A representative sample of these results will be shown with emphasis on the shear Alfvén modes. Comparison of the full system for alpha particles will be made with simplified models now being investigated numerically to study both non-linear fluid and kinetic effects.

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Unified Plasma Fluid/Kinetic Equations for Tokamak Microinstability and Turbulence Studies*

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Unified fluid/kinetic equations for the plasma perturbed density ($\tilde{n}$), parallel flow velocity ($\tilde{u}_{\|}$) and temperature ($\tilde{T}$) are developed by calculating the fluid moment closure relations kinetically. To calculate closure relations for $\mathbf{b} \cdot \nabla \cdot \tilde{\mathbf{\Pi}}_{\|}$ and $\nabla \cdot \tilde{\mathbf{q}}$ to be used in a set of perturbed fluid equations for $\tilde{n}$, $\tilde{u}_{\|}$ and $\tilde{T}$, a linearized drift-kinetic Chapman-Enskog-type equation is solved in a sheared slab geometry. A moment approach and a physically realistic collision operator (Lorentz scattering operator plus the momentum restoring terms) are used. The resultant closure relations for $\tilde{\pi}_{\|}$ and $\tilde{q}_{\|}$ possess both the fluid and kinetic properties. In the fluid collisional limit the equations reduce to the well-known Braginskii equations. In the adiabatic limit they reproduce the usual kinetic results, including Landau damping. It is shown that the Chapman-Enskog-type approach is more compatible with a fluid-like description of plasmas than the usual gyrokinetic approach. Remarkable simplification of these complicated closure relations is achieved. The results are compared with other recently developed Landau damping models [1] and shown to be more accurate and complete.

The unified fluid/kinetic equation set is valid for arbitrary values of ν/ω (collisionality) and $\omega/k_{\|}v_t$ (strength of Landau damping). Applications of this set of equations show that many well-known microinstabilities (collisionless and dissipative electron drift instabilities, η_i modes, micro-tearing modes, etc.) are covered by these equations when appropriate limits are taken. The new perturbed Ohm's law obtained extends the Hazeltine, Dobrott and Wang's generalized Ohm's law [2] to arbitrary $\omega/k_{\|}v_{te}$. Generalized nonlocal eigenvalue equations for electron and ion drift type modes and micro-tearing type modes are presented. The feasibility of including magnetic trapped particle effects in the fluid equations through the closure equations and thus the derivation of trapped-particle instabilities [3] by this procedure, is also demonstrated. Taking into account only the major nonlinearities, these fluid/kinetic equations extend the Hasegawa-Wakatani drift wave turbulence equations [3] into regimes of arbitrary ν/ω and $\omega/k_{\|}v_t$.

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Studies of $m = 1$ Modes in High-Temperature Plasmas with a Four-Field Model*

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The $m = 1$ mode in high temperature plasmas is examined using a simple four-field model of tokamak dynamics derived by Hazeltine, Hsu, and Morrison[1]. The model extends the usual reduced MHD equations by including FLR effects, finite electron and ion drift frequencies, and long-mean-free-path electron dynamics. It is shown that, despite its simplicity, it reproduces with remarkable accuracy results obtained with more sophisticated kinetic treatments in various collisionality regimes. In particular, we recover:

1. In the collisional regime, the dispersion relation of Ara, Basu *et al.*[2] for the resistive $m = 1$ modified by diamagnetic drifts,
2. Hamh's dispersion relation[3] for the semi-collisional $m = 1$ mode[4], and
3. Porcelli and Berk *et al.*'s dispersion relation[5,6] for the collisionless $m = 1$ mode.

The effects of parallel compressibility on the $m = 1$ mode in the collisional, semi-collisional and collisionless regimes are also discussed. Coupling to the ion sound waves is found to be weakly destabilizing in the collisional regime, and stabilizing in the semi-collisional and collisionless regimes. Results from nonlinear calculations of the semi-collisional and collisionless $m = 1$ modes will be presented.

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Rotation Velocity Profile Control by Slow Electromagnetic Waves

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Confinement of tokamak plasmas may depend on the rotation velocity profile, since velocity shear may suppress fluctuations [1]. Slow electromagnetic waves are found to be a potentially attractive means for control of the velocity profile. The idea is to use antenna currents proportional to $\cos(m\theta + n\phi + \omega t)$ for perturbing an axisymmetric tokamak. Here, θ and ϕ are the poloidal and toroidal angles of a tokamak, m and n integers, ω and t are frequency and time. The perturbation results in formation of islands at the surface where the safety factor, q, equals m/n; the islands rotate with the toroidal angular velocity ω/n. In the MHD limit, plasma flow must be tangential to flux surfaces. Away from the island surface, the configuration may be considered axisymmetric; here, flow in the toroidal direction is impeded only by ordinary viscosity, while flow in the poloidal direction, in addition, is impeded by the strong, neoclassical effect of collision between flowing and trapped particles. Therefore, here the flow is almost entirely in the toroidal direction. Plasma inside the islands is similarly inhibited from flowing in the "helical" direction of the islands because of trapped particles, and flow perpendicular to the helical direction is inhibited by ordinary viscosity when the islands are narrow. Therefore, one may expect that the plasma inside the rotating islands follow their rotation. The islands thus may act as "stirrers" immersed in the plasma.

The range of validity of these concepts was explored by studying helically symmetric equilibria for which plasma inside islands is exposed to forces imitating the viscous and neoclassical forces acting on the plasma inside rotating tokamak islands. It is found that the island width decreases as the total force is increased and that a maximum force is found as a function of the initial island width. It is conjectured that for island rotation velocities above that corresponding to the upper force limit, nonstationary flows which possibly break the assumed symmetry may be found in a real plasma. The upper limit of the force is large enough that even narrow islands may produce a large shear in the flow.

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FAST ELECTRON TRANSPORT IN CURRENT DRIVE*

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ABSTRACT

In steady state current drive the toroidal current in tokamaks is sustained by fast electrons which absorb energy and momentum from externally injected waves. The dynamics of the fast electron population is well described by balancing wave induced quasilinear diffusion with collisional slowing down and pitch angle scattering off of fixed Maxwellian field particles. Using Hamiltonian gyro-kinetic theory [1], we generalize the quasilinear-Fokker-Planck formulation to include the wave induced radial transport of fast electrons.

We have applied this approach to lower-hybrid current drive (LHCD). For efficient LHCD the wave spectrum is typically launched at low parallel indices (i.e. $ck_{\|}/\omega$ near the accessibility limit), for which the electron Landau damping is very weak. Toroidal ray tracing shows that under such circumstances, the ray trajectories of the waves can make several passes through the plasma during which time the parallel wave number ($k_{\|}$) upshifts until the fields are Landau damped (hence filling the "spectral gap"). The fields develop a large poloidal component, associated with the upshift in $k_{\|}$, which leads to a radial $E \times B$ drift of resonant electrons. We have studied this effect by coupling the quasilinear-Fokker-Planck equation to a toroidal ray tracing code [2], which determines the fields. Two types of radial flows are obtained: (i) a convective flow derived from the collisional slowing down of fast electrons in the presence of an asymmetric poloidal wave spectrum, and (ii) a collisionless diffusive flow proportional to the width of the poloidal spectrum. The convective flow is outward when the poloidal spectrum is upshifted to fill the spectral gap. Simulations of Alcator C and JT60, show that the radial convection velocity has a broad maximum of nearly 1 m/sec and is independent of the amplitude of fields. In both cases, the radial diffusion is found to be highly localized near the magnetic axis. For JT60, the peak of the diffusion profile can be quite large, nearly 1 m^2/sec.

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Drift and Diffusive Losses of Alpha Particles Caused by Toroidal Alfvén Eigenmodes

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Finite amplitude toroidal Alfvén eigenmodes (TAE or gap modes) cause losses of super-Alfvénic ($v_{\|\alpha} \geq v_A$) α-s on theoretical grounds [1]. Recent tangential NBI experiments on DIII-D and TFTR with confirming results have reinforced interest in this problem. Since the gap mode has at least two dominant poloidal harmonics m for a given toroidal mode number n the α guiding center motion can produce stochastic diffusion in phase space above a critical perturbation amplitude $\tilde{B}/B_0$ (where B_0 is the equilibrium field). Below this threshold resonant α-s satisfying $\omega - k_\| v_\| - \vec{k}_\perp \cdot \vec{v}_D \simeq 0$ can experience secular radial drifts across the classical orbit loss boundaries of energetic ions (whose orbit width is finite, e.g. counter-going passing ions with pitch angle near the trapped-circulating separatrix). Using a Hamiltonian guiding center code and linear mode structure of the TAE obtained for a CIT equilibrium with the Nova K code and $\tilde{B}/B_0$ as a free parameter we find for a random ensemble of α-s

(i) Stochastic diffusion is clearly established at $(\tilde{B}_r/B_0)_{gap} = 2 \times 10^{-3}$ (but the radial peak location of $\tilde{B}_r$ need not coincide with the gap location).

(ii) Toroidal angular momentum diffusion $D_{P_\varphi P_\varphi}$ scales $\propto B_r^2$ and inversely with the square of the plasma current.

(iii) Depending on (E, μ) and mode amplitude, the P_φ vs. φ (toroidal angle) action-angle plot shows stochastic regions clearly bounded by KAM surfaces. Consequently, α-s in the stochastic domain can remain confined (although diffusing within a bounded region).

(iv) An α particle whose unperturbed P_φ is close enough to a loss boundary can drift into the loss region if the corresponding KAM surface touches the loss boundary at a $\tilde{B}_r/B_0$ value even below the stochastic threshold. Such losses scale as B_r (not B_r^2) cf. [1] and tend to vanish after a transient unless α-s are replenished by the fusion source or collisions. (The stochastic threshold depends on (E, μ, P_φ) and the radial profile of the TAE which typically peaks in the plasma core. Thus the core can be stochastic while the plasma edge still possesses KAM surfaces which cannot be crossed).

(v) New guiding center simulation results for an ensemble of α-s will be shown. In order to expose the transport mechanisms α-s crossing the loss boundary are not replaced by new α-s at their original phase space point at birth. At $(\tilde{B}_r/B_0)_{gap} \geq 10^{-3}$ the ensuing fast α confinement time can approach the slowing down time.

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QUASILINEAR EVOLUTION OF THE BEAM-PLASMA INSTABILITY IN THE TURBULENT TRAPPING REGIME

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Abstract

We use a self consistent hamiltonian formulation[1] of the beam plasma instability problem to test the recent proposition[2-5] that quasilinear theory, by failing to account for mode-mode coupling, underestimates the Landau growth rate in the turbulent trapping regime, where the resonance broadening frequency $\nu = (k^2 D_{ql})^{1/3}$ is larger than the quasilinear growth rate γ_{ql}. Initial results show that mode-mode coupling plays an important role in the development of the system, but do not find an enhancement of the quasilinear growth rate.

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Connection between Recurrence Time Statistics and Anomalous Transport[1]

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For a model stationary flow with hexagonal symmetry, the recurrence time statistics are studied. The model has been shown to have a sharp transition from normal to anomalous transport. Here it is shown that this transition is accompanied by a correspondent change of the recurrence time statistics from "normal" to "anomalous." The latter one displays the existence of a power tail. Recurrence time statistics provide a local measurement of anomalous transport that is of practical interest.

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The Unstable $l = 1$ Diocotron Mode in a Hollow Electron Column

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Abstract

A radial eigenvalue code in a collisionless fluid model with finite temperature for axisymmetric, magneticaly confined electrons predicts an exponentially unstable mode with properties in reasonable agreement with experimental results reported by Driscoll [*Phys. Rev. Lett.* **64**, 645 (1990)]. The unstable mode can be identified with a nonsmooth perturbation that is a stable mode in drift models but is destabilized by finite temperature effects. Identification of the physically meaningful modes from the code output and their dependence on temperature will be discussed.

LINEAR AND NONLINEAR EVOLUTION OF RESISTIVE BALLOONING MODES WITH KINETIC CORRECTIONS

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We have developed a 3-D magneto-fluid code to study the linear and nonlinear evolution of resistive ballooning modes including some kinetic effects in a toroidal geometry. The physical model employed is basically a four-field model for tokamak plasma dynamics [1] and it allows for i) slow temporal evolution at the diamagnetic drift frequency, ii) pressure gradient corrections in a generalized Ohm's law, iii) plasma compressibility, and iv) thermal conductivity. All four field quantities (poloidal magnetic flux, electrostatic potential, parallel flow velocity, and electron pressure) are finite-differenced in the radial direction and Fourier-analyzed in the poloidal and toroidal directions. The set of equations is advanced numerically as an initial value problem for both linear and nonlinear runs. A severe temporal step size restriction for numerical stability imposed by a coupling between the parallel electron pressure gradient term in the Ohm's law and the finite Larmor radius (FLR) correction term to parallel compressibility has been removed by implementing a fourth order semi-implicit scheme [2].

We have demonstrated that the FLR effect tends to reduce the linear growth rate of resistive ballooning modes of low to medium mode numbers. When thermal conductivity is also considered, the FLR effect is shown to further reduce the linear growth rate of the resistive ballooning modes. At least in one case, complete stabilization of the resistive ballooning modes is observed. Quasilinear and nonlinear simulations are under way. Preliminary results suggest a significant spectral broadening. To facilitate further work, the code will be modified to adopt a coordinate transformation which shifts the coordinate origin of a poloidal cross section to the location of the equilibrium magnetic axis [3].

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Semi-Implicit Gyrokinetic Particle Simulation*

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The gyrokinetic simulation technique[1] has proven to be an efficient method for simulating low- frequency drift-wave instabilities and the transport associated with them. The standard gyrokinetic models treat electrons in the drift-kinetic limit because of their very small Larmor radius and ions in the gyrokinetic limit. These treatments analytically remove the cyclotron timescales, but retain the important drifts, ion polarization and finite-Larmor-radius effects, and electron and ion Landau resonances. However, with realistic mass ratios, the characteristic time scales for accurately following the electrons are much shorter than for following the ions and the development of instabilities like the trapped-particle modes and ion-temperature-gradient modes. As a result, if traditional explicit time-differencing is used for a numerical solution of the gyrokinetic equations and if good space-time resolution and adequate signal-to-noise ratios are demanded, simulations of these instabilities for large systems with weak gradients are very costly.

We have recently implemented a semi-implicit, orbit-averaged algorithm in a two-dimensional gyrokinetic code, which may dramatically improve the efficiency of fully nonlinear gyrokinetic particle simulation with kinetic electrons and ions.[2] The semi-implicitness allows us to relax the traditional stability condition on the timestep and perform stable and accurate numerical averages of the electron current density required in the field equations. This enables the use of large timesteps in the ion advance and the field solve, as well as a significant reduction of particles modeling the electrons. One expects a large improvement in the overall code efficiency scaling as the square root of the electron-ion mass ratio. We report our progress with the new code, our experience with noise issues in gyrokinetic simulation, and application of our two-dimensional code to the study of ion-temperature-gradient modes in anisotropic, non-Maxwellian plasmas to model strongly heated plasmas.

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ELECTROMAGNETIC WAVE SCATTERING FROM MAGNETIC FLUCTUATIONS IN TOKAMAKS

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Abstract

Cross sections are calculated for electromagnetic wave scattering and mode transformation from magnetic and density fluctuations in the vicinity of the principal electron cutoffs and resonances in a homogeneous plasma. For the special case of scattering perpendicular to the magnetic field, density fluctuations scatter ordinary to ordinary and extraordinary to extraordinary modes - but cannot transform these modes. On the other hand, magnetic fluctuations perpendicular to the field can transform modes but cannot scatter on a single branch. For incident frequencies on the order of the electron plasma frequency or gyrofrequency, the cross sections for scattering and transformation due to field and density fluctuations have a similar value. Estimates are given for scattering in a tokamak plasma with special emphasis on the question of how to detect and localize magnetic field fluctuations. Toroidal effects are handled by ray tracing. Ray tracing calculations and estimates of practical limitations on detection technique show that magnetic fluctuations can be detected and localized by this method - even when the magnetic fluctuation levels are orders of magnitude lower than the density fluctuations.

Toroidal Alfvén Eigenmodes in a Finite Pressure Equilibrium*

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The combined effects of finite pressure and finite Bloch shift, θ_k, on the toroidal Alfvén eigenmodes have been studied both analytically and numerically employing the $s - \alpha$ model equilibrium. It is demonstrated that, in the s, $\alpha > 1$ limit, the even mode coalesces with the continuous shear Alfvén spectrum at $\alpha = \alpha_c$ which agrees with the ballooning-mode first stability boundary asymptotically. As to the odd mode, it is found to exist for $\alpha \geq s > \alpha_c$; i.e., inside the ballooning-mode unstable regime. The implications of the present results to damping via resonant Alfvén absorption and stability properties will be discussed.

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SIMULATION OF THE THIN SHELL AND SECONDARY SHELL HBTX1C EXPERIMENTS

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Three-dimensional, nonlinear, resistive MHD numerical simulations of the HBTX1C and 1C+ (secondary shell) thin shell RFP experiments are reported. These calculations were performed with realistic aspect ratio, and with both artificially low ($S = 10^4$) and realistic ($S = 5\times10^5$) plasma resistivity. The shell time constant was kept artifically low (τ_s = .025 msec) for reasons of numerical efficiency. (This should not affect the conclusions presented herein, as the final plasma states in the presence of a resistive shell are known to be independent of the shell time constant.) We find that both the loop voltage and fluctuation levels levels are higher in 1C than in 1C+, and both are higher than in HBTX1B (with a thick shell). Premature termination due to large increases in non-Spitzer loop voltage is observed in the 1C simulation. This termination is accompanied by a growing $m = 1$, $n = -5$ mode that is locked to the wall, and becomes toroidally localized as it grows. Similar initial behavior is observed in the 1C+ simulations. However, the presence of the secondary shell apparently makes the modes saturate at an amplitude low enough to allow the discharge to continue, and to reach an eventual quasi-steady state. External kink modes are prominent at high S; these modes are apparently inhibited in the low S simulations. Detailed comparisons with experimental data are made.

THEORY-BASED TRANSPORT SIMULATIONS OF TOKAMAK TEMPERATURE PROFILES

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The evolution of temperature profiles in tokamak discharges has been simulated with the 1-1/2-D BALDUR transport code using a combination of theory-based transport models.[1–4] The present version of the transport model consists of effective thermal diffusivities resulting from trapped electron modes and ion temperature gradient (η_i) modes, which dominate in the core of the plasma, together with resistive ballooning modes, which dominate in the periphery. Scalings with plasma current, heating power and density are illustrated with a variety of steady state TFTR L-mode simulations.

It is found that L-mode and H-mode plasmas can be simulated with the same core transport model, with changes only at the edge of the plasma. Scaling with elongation is calibrated against JET and DIII-D simulations. An extrapolation to BPX (formerly CIT) will be presented using the same transport model.

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A Quasilinear Description for Fast Wave Minority Heating Permitting Off Magnetic Axis Heating in a Tokamak*

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By keeping only the essential physical effects the simplest possible quasilinear description of fast wave minority heating in a tokamak is presented in a tractable form suitable for convenient numerical implementation. The resulting quasilinear operator retains all trapped and passing particle effects and permits the minority heating resonance line to be offset from the magnetic axis. The quasilinear diffusion coefficient is shown to depend on pitch angle and inverse aspect ratio in rather different ways for a high and low field side off-axis resonance. Rather than averaging the infinite, homogeneous quasilinear operator, the derivation is carried out in tokamak geometry to properly treat the merging of distinct rf-particle interaction regions. Merging occurs when the banana tips of trapped particles are in the vicinity of the minority resonance, or, for both trapped and passing particles, when the minority resonance is tangent or nearly tangent to a flux surface. A smooth transition from distinct uncorrelated rf wave-particle interactions to the correlated rf interactions that occur at merging can be made by using a phenomenological collision model for gyrophase diffusion due to pitch angle scatter.

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A GENERALIZED δf METHOD

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A new approach for implicit PIC plasma simulation is described. In this method, only the deviation of the true distribution f from a *local* Maxwellian $f_M(\mathbf{x},t)$ is represented by PIC methods. The parameters of the Maxwellian (density, mean velocity, temperature) satisfy the usual moment equations, which are coupled to Maxwell's equations and differenced implicitly. To close the moment equations, the traceless stress and heat flux are evaluated on the mesh from δf, the difference between f and f_M by advancing a collection of simulation particles and using PIC methods. A 1-D electromagnetic, two-fluid code based on this algorithm has been constructed and has demonstrated several features of the method. First, noise is greatly reduced for situations in which the plasma remains close to LTE. Second, linear numerical stability seems insensitive to methods used to evaluate the PIC related moments. Thus, for example, substepping, orbit averaging, and gyroaveraging have been demonstrated to give stable time advance schemes. Finally, nonlinear stability depends on maintaing consistency between the particle and moment data. These features are illustrated by examples of the simulation of linear waves. Extension of this method to 3-D plasma simulation is described.

Bootstrap Current and Viscous Forces in D-T Plasmas*

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Recently, a Chapman-Enskog-like approach [1] has been developed by treating the kinetic and eight fluid (density $n(\vec{x},t)$, temperature $T(\vec{x},t)$, momentum $m\vec{V}(\vec{x},t)$ and heat flux $\vec{q}(\vec{x},t)$) equations consistently. Coulomb collisions of multiple ion species are allowed in a density, momentum and energy conserving collision operator model. Using this formalism, the flux-surface-averaged parallel viscous stress forces $\langle \vec{B} \cdot \vec{\nabla} \cdot \mathbf{\Pi}_{\|} \rangle$ and $\langle \vec{B} \cdot \vec{\nabla} \cdot \Theta_{\|} \rangle$ can be directly derived from the kinetic solution in the banana (low collisionality) regime. Applying this formalism to plasmas with deuterium and tritium ion species, a case where the masses of the two ion components are not very dissimilar, the viscous forces $\langle \vec{B} \cdot \vec{\nabla} \cdot \mathbf{\Pi}_{\|} \rangle$ and $\langle \vec{B} \cdot \vec{\nabla} \cdot \Theta_{\|} \rangle$ are calculated by taking a proper untrapped particle "flow" moment of the bounce-averaged Chapman-Enskog-like version of the drift-kinetic equation. The collisional forces including trapped particle effects are evaluated from the lowest subsidiary order (in ν/ω_b, ν = collision frequency, ω_b = bounce frequency) kinetic solution. The effects of similar mass multiple ion species on the bootstrap current in a tokamak plasma will be presented.

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Spectrum of Turbulent Fluctuations in the Presence of Self-Induced Poloidal Shear Flow

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It has been shown that the sheared poloidal flow observed in H-mode discharges is capable of suppressing the level of turbulent fluctuations in generic and edge-specific models[1,2]. These calculations establish the role of sheared poloidal flow in reducing the overall fluctuation level, but do not address its effect on the spectral distribution of turbulent energies. In this work, we determine the wavenumber spectrum of turbulence in the presence of poloidal flow shear by solving the two-point evolution equation[3].

We utilized a simple Kadomtsev-Pogutse model based on the dissipative trapped electron mode. This model allows self-consistent determination of turbulently self-generated poloidal flow and flow suppressed saturated turbulence levels. Previous work has established the linear stability, linear and nonlinear mode structure, and saturation levels of weak and strong turbulence for this model.

The two-point fluctuating density correlation equation is found to have features which have not been confronted in previous two-point analyses[3]. In particular, the E×B nonlinearity (which dominates the polarization drift nonlinearity for $k_\theta \rho_s < 1$) has nonlinear transfer which is both local and nonlocal in wavenumber space. The local transfer is represented by the familiar relative diffusion process which conserves internal energy by vanishing as the relative separation goes to zero. The nonlocal transfer is shown to act as a source in the two-point equation, a role which is consistent with nonlocality in k-space. The solution of the two-point equation is presented, and the spectrum, obtained as the Fourier transform of the two-point solution, is given. The results are compared with simulations which incorporate the E×B nonlinearity.

*Supported by US DOE contracts DE-FG02-89ER-53291 and DE-FG03-88ER-53275

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Feedback Control of the Thermonuclear Thermal Instability with A Poloidal Divertor Suppressor

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A novel concept of burn control in a tokamak reactor is discussed where the poloidal divertor is used as a feedback suppressor. When an electrical voltage is applied to the divertor plates, an electrical current flows along the magnetic field lines in the scrape-off layer. This current causes an additional electron heat flow which is collected at the divertor plates. In turn it affects the power balance between the radial power loss and the parallel heat flow in the scrape-off layer. In particiular, when there is a positive temperature perturbation in a thermal instability, if a positive voltage is applied at the divertor plates, the resulting additional electron heat flow to the divertor will tend to reduce the positive temperature perturbation. This process is realized via a feedback system where the feedback voltage on the divertor plates is derived from the ion temperature sensor via a D-T neutron emission diagnostic, after appropriate amplification and phase shift. Typical feedback gain and phase requirements have been derived and the feedback power level of a few MW is estimated for ITER like parameters. The completely electrical nature, simplicity and non-interference in the vital systems for heating and fueling of the tokamak, make this scheme technologically attractive.

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STOCHASTIC BROADENING IN THE DIVERTOR REGION USING THE STANDARD MAP

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Although perturbations give a stochastic region about a separatrix, it is not clear whether the image of the separatrix on the strike plate of a tokamak divertor is broadened or becomes a complicated curve[1]. To address this issue we are using the standard map[2] and a continuous analogy. When the parameter k of the map is close to unity, the topology of a double null divertor is faithfully reproduced. To lead trajectories into the separatrix region, we start in a region of good surfaces. But, in addition to the standard map we add a small diffusive term to the iterations. We are studying the width of the region intercepted by the field lines on the equivalent of the divertor strike plates in the limit as the diffusion coefficient goes to zero. This work is supported by DoE under its grants DE-FG05-88ER53265 and DE-FG05-90ER54106.

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Equilibrium Current Profiles in Tokamaks+

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Several experiments have shown quantitative agreement between the average resistivity $\eta_{||}$ and the neoclassical theory [1]. However, when the neoclassical resistivity is used together with the Ohm's Law $E_{||} = \eta_{||} J_{||}$ to calculate the equilibrium current density $J_{||}$ in Ohmically heated plasmas, strange radial profiles of $J_{||}$ result. These profiles are "strange" in the sense that they are sharply peaked and cusp-like near the magnetic axis, and quite narrow overall, when the electron temperature is well behaved. To accomodate the total current, such profiles require unreasonably low values of q_o.

To resolve this problem while retaining agreement with measurements of the average resistivity, a model [2] has been proposed in which the anomalous transport of the electron thermal energy and that of the current density are intrinsically coupled, on the basis that $E_{||}$ is the source for both when no injected heating is present . A new thermal-viscous transport coefficient L_e is postulated, with the equilibrium transport relations:

$$EJ = -\nabla \cdot [\kappa_e \nabla T - \frac{1}{2} L_e J \mathbf{G}] \qquad\qquad E - \eta J = -\nabla \cdot (L_e \mathbf{G})$$

Here $\mathbf{G} = \nabla J - (3J/2T)\nabla T$ and κ_e is the thermal conductivity, taking the Coppi-Mazzucato-Grüber form. Following the Principle of Profile Consistency, a proportionality between L_e and κ_e, $L_e J^2 = 4\lambda \kappa_e T/3$, where λ is a finite numerical factor, can be justified. From these assumptions, a "Profile Equation" is obtained, relating the electron temperature and current density profiles

$$J(x) = J_o H(x) exp(-\frac{3}{2}\alpha_T x) \qquad\qquad T(x) = T_o H(x)^{(\lambda/(\lambda+1))} exp(-\alpha_T x)$$

to λ, the enhancement to the Spitzer resistivity $\Sigma = \eta/\eta_{sp}$, and the (unknown) electric field enhancement $\hat{E} = E/E_{sp}$, where $E_{sp} = \eta_o J_o$ and $x = r^2/a^2$:

$$\frac{1}{H}\frac{dH}{dx} = -\frac{3}{4}\alpha_T (1 + \frac{1}{\lambda}) H(x) exp(-\frac{3}{2}\alpha_T x) \frac{\int_0^x d\xi [1 - \Sigma(\xi) H(\xi)^{(1/(1+\lambda))} \hat{E}^{-1}]}{\int_0^x d\xi H(\xi) exp(-\frac{3}{2}\alpha_T \xi)}$$

In this work [3], we solve the Profile Equation numerically for several resistivity models, including one obtained from experimental data, subject to the global condition

$$\int_0^{a^2} (E - \eta J) dr^2 = 0$$

while treating E as an eigenvalue. We find current profiles that are well behaved near the axis in all cases. In addition, the resulting electron temperature profiles are found to be quite insensitive to λ, in agreement with the Principle of Profile Consistency. Finally, analytical solutions elucidating the behavior of the equation are discussed.

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EXTENSIONS OF NEOCLASSICAL TRANSPORT THEORY FOR COLLISIONAL IONS IN STRONGLY-ROTATING TOKAMAK PLASMAS

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The kinetic equation is solved for a collisional ($\nu_* > 1$) ion species in a strongly rotating ($v_\phi \sim v_{th}$) plasma, using a poloidal gyroradius expansion and a decomposition of the first-order distribution function $f_1 = \bar{f}_1 + \tilde{f}_1$ into gyroangle-averaged ($\bar{f}_1$) and gyroangle-dependent ($\tilde{f}_1$) components. The development parallels that of Hinton-Wong [1], who treated ions with $\nu_* \simeq 1$.

The lowest order momentum flux is evaluated from

$$\overleftrightarrow{\pi}(f_1) \equiv m \int (\vec{v}\vec{v} - \frac{1}{3} v^2 \overleftrightarrow{I}) f_1 d^3v \equiv \overleftrightarrow{\pi}(\bar{f}_1) + \overleftrightarrow{\pi}(\tilde{f}_1), \tag{1}$$

and the corresponding viscous torque is $\langle R\hat{n}_\phi \cdot \nabla \cdot \overleftrightarrow{\pi} \rangle$. The gyroviscous torque [2] is recovered from $\overleftrightarrow{\pi}(\tilde{f}_1)$, and a new "rotational" viscous torque of collisional origin is obtained from $\overleftrightarrow{\pi}(\bar{f}_1)$ which has the same form as the gyroviscous torque

$$\langle R\hat{n}_\phi \cdot \nabla \cdot \overleftrightarrow{\pi} \rangle \simeq -\frac{1}{2} \tilde{\theta} \frac{r}{R} \frac{\partial}{\partial r} (\eta_4 v_\phi), \tag{2}$$

where $\tilde{\theta}$ is an involved function of poloidal asymmetries in density, velocity and flux surface geometry and $\eta_4 = p/\Omega$. A consistent solution demonstrates that these asymmetries are $O(\epsilon)$ for ions with ($v_\phi \sim v_{th}, \nu_* > 1$), in which case $\tilde{\theta} \sim O(1)$.

The lowest order energy flux is evaluated from

$$\langle \nabla\psi \cdot \vec{Q}(f_1) \rangle \equiv \langle \int (\frac{1}{2} mv^2 + e\tilde{\Phi})(\nabla\psi \cdot \vec{v}) f_1 d^3v \rangle \equiv \langle \nabla\psi \cdot \vec{Q}(\bar{f}_1) \rangle + \langle \nabla\psi \cdot \vec{Q}(\tilde{f}_1) \rangle, \tag{3}$$

which is related to the corresponding divergence of the energy flux by

$$\langle \nabla \cdot \vec{Q} \rangle = \frac{1}{RB_\theta r} \frac{\partial}{\partial r} (r \langle \nabla\psi \cdot \vec{Q} \rangle). \tag{4}$$

We find a new "rotational" contribution

$$\langle \nabla \cdot \vec{Q}(\bar{f}) \rangle \simeq -\frac{5}{4} \frac{r}{R^2} \left[\tilde{\theta}_A \frac{\partial}{\partial r} (\eta_4 v_\phi^2) + \tilde{\theta}_B \frac{\partial}{\partial r} (\eta_4 \frac{T}{m}) \right] \tag{5}$$

of a collisional origin, where $\tilde{\theta}_{A/B}$ are involved functions of poloidal asymmetries.

We note that momentum confinement times, τ_ϕ, constructed from Eq. (2) with $\theta \sim O(1)$ agree reasonably well with measured values [3, 4]. We further note that when the ion energy confinement time, τ_i, is constructed from Eq. (5) with $\tilde{\theta}_{A/B} \sim O(1)$, the ratio $\tau_\phi / \tau_i \sim O(1)$ independent of plasma parameters, a feature observed in many tokamak experiments.

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PHYSICS OF A HIGHLY NONEQUILIBRIUM ION DISTRIBUTION: THE POLYWELL™/SCIF*

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The Polywell™/SCIF fusion confinement concept,[1] in which magnetically confined electrons form a spherical potential well which causes the ions to flow to the center of the sphere, is characterized by a highly nonequilibrium ion velocity distribution. This distribution must in fact be maintained in a state far from thermal equilibrium in order for the ions to converge to a dense core at the center of the sphere, which is required for the success of the concept. In this paper we calculate the effects of some of the processes which tend to drive the ions toward thermal equilibrium. These processes include collisional upscatter in energy, collisional isotropization, and turbulent distortion and relaxation of the ion distribution. The problem is made more complicated and much more interesting from a theoretical point of view because of the strong variations in the density and velocity distributions at different radii. We present an analytic model for this variation, which is the starting point for the other calculations.

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Gyrokinetic Particle Simulation of Ion Temperature Gradient Instabilities in 3D Toroidal Geometry*

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We are are developing a three dimensional toroidal gyrokinetic particle code to study quasineutral tokamak physics. Here we present the current status of code development and report initial success modeling the ion temperature gradient mode. For this problem, the system is electrostatic and the electrons are assumed adiabatic ($\delta n_e = n_0 e\bar{\Phi}/T_e$). The ions are evolved with the full gyrokinetic equations of motion:

$$\dot{v_{\|}} = -\left[\hat{\mathbf{b}}_0 + \frac{v_{\|}}{\Omega_0}\hat{\mathbf{b}}_0 \times (\hat{\mathbf{b}}_0 \cdot \nabla)\right] \cdot \left[\frac{v_\perp^2}{2}\nabla \ln B_0 + \frac{q}{m}\nabla\bar{\Phi}\right], \quad (1)$$

$$\dot{\mathbf{x}} = v_{\|}\hat{\mathbf{b}}_0 + \frac{v_{\|}^2}{\Omega_0}\hat{\mathbf{b}}_0 \times (\hat{\mathbf{b}}_0 \cdot \nabla)\hat{\mathbf{b}}_0 + \frac{v_\perp^2}{2\Omega_0}\hat{\mathbf{b}}_0 \times \nabla \ln B_0 + \frac{c}{B_0}\hat{\mathbf{b}}_0 \times \nabla\bar{\Phi} - \frac{q}{m\Omega_0}\hat{\mathbf{b}}_0 \times \mathbf{K}\bar{\Phi}, \quad (2)$$

where the last term in Eq. (2) is a multiple scale expansion used to model the equilibrium spatial temperature and density profiles. B_0 and $\hat{\mathbf{b}}_0$ are the fixed equilibrium magnetic field magnitude and direction. We use a slab like coordinate system which is suitable for Fourier decomposition of the field equation. The coordinates (x, y, z) in terms of the usual toroidal coordinates (r, θ, ψ) are: ($x = r\cos\theta, y = r\sin\theta, z = -(R_0 - a)\psi$). Using these coordinates and assuming $k_{\|} \ll k_\perp$ one can transform the field equation to obtain:

$$-\frac{\tau}{\lambda_{De}^2}(1 - \Gamma_0(k_\perp\rho_i))\Phi(k_\perp, z) = -4\pi e\left[\delta\bar{n}_i(k_\perp, z) - n_0\frac{e\Phi(k_\perp, z)}{T_e}\right], \quad (3)$$

where higher order terms have been neglected. We will present results of the η_i mode simulation showing the nonlinear evolution of potential, density, current, pressure and heat flux; and study the the effects of trapped and passing ion orbits on linear stability and the saturation of these quantities. In the future, we plan to add drift kinetic electrons and finite beta effects ($\delta\mathbf{B}$) to the toroidal code greatly extending it's applicability.

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Form Invariance in Convective-Diffusive Systems with Applications*

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Based on a physically reasonable model of a convective-diffusive system, we have been able to obtain simple closed form expressions for the time evolution of the impurity profiles. The profiles show a form invariance, the canonical form being $\sim e^{-\alpha(e^{-\tau},\cdots)r^2} I_0(\beta\alpha r)$ where I_0 is the modified Bessel function, and α depends on time $(e^{-\tau})$, the diffusion coefficient $\mathcal{D}_0$, and the convection parameter v_0. These explicit solutions can be used to model a wide variety of transport phenomenon. As an illustration, we present detailed comparison with the pulsed impurity injection experiments on TEXT.

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ION AND ELECTRON HEATING IN RESISTIVE MHD TURBULENCE

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One puzzling observation in certain ohmically heated plasmas (RFP core and tokamak edge plasmas) is that $T_i > T_e$ (where T_i and T_e are the ion and electron temperatures). This contradicts the generally accepted heating scenario wherein the equilibrium current ohmically heats the electron distribution (via the classical Spitzer resistivity), and the ions are then heated through collisions with the electrons. Such a process would produce T_i that is at most equal to T_e, since collisional heat exchange is constrained by the Zeroth Law of Thermodynamics. Thus, it appears that there can be a significant ion heat source in plasmas that is poorly understood. One common feature of the RFP core and the tokamak edge is rather large amplitude electromagnetic turbulence (often believed to be tearing modes in the former, and rippling modes in the latter), suggesting that the anomalous ion heat could be coming from viscous damping of the energy in such turbulence.

In this work, we calculate the ion heating coming from the viscous damping of a spectrum of tearing modes (in both linear and Rutherford regimes), and from rippling modes. It is found that ion heating can indeed be large (comparable to or larger than the resistive damping of the same modes, which deposits energy dominantly in the electrons), and can provide a reasonable explanation for the observed anomalies. This suggests that viscous ion heating could well play an important role in the overall energy budget, and thus in anomalous heat transport.

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Further Considerations of Large Aspect Ratio High Beta Equilibrium and Stability*

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In our previous work we derived analytic equilibria with arbitrary $p(\psi)$ and $q(\psi)$ profiles for arbitrarily shaped large aspect ratio tokamaks at high beta ($\beta >> \varepsilon/q^2$). We show that, for our equilibria, external measurements of the magnetic field yield information about the pressure but <u>not</u> $q(\psi)$. We also consider the Mercier and ideal ballooning stability of our equilibria. All of our equilibria are Mercier stable; ballooning stability, however, is not guaranteed. Our results are at betas above those currently accessible with numerical codes.

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NONLINEAR GYROKINETIC THEORY OF ION TEMPERATURE GRADIENT DRIVEN MODES WITH VELOCITY SHEAR

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A nonlinear gyrokinetic equation is derived for a plasma with radially sheared rotation. In the derivation, the action–variational Lie perturbation method is utilized in order to preserve the Hamiltonian structure of the original Vlasov–Poisson system. A crucial physics effect of sheared rotation is that the axis of the particle gyration in the rotating plasma frame is aligned along the "effective" magnetic field $\vec{B} + (Mc/q)\nabla \times \vec{v}_0(r)$. This representation provides a natural description of the Kelvin–Helmholtz–like driving mechanism.

The nonlinear equation derived is applied to the investigation of Ion Temperature Gradient (ITG) driven turbulence in the presence of sheared rotation.

In particular, the radially dependent Doppler–shifted frequencies of the ITG–modes allow the weak turbulence approach to be more readily applicable by enhancing the effective dispersion. An appropriate form of the wave–kinetic equation is derived in a sheared slab geometry to address this problem. Attention is focused on the relative importance of the destabilizing influence of the Kelvin–Helmholtz–like drive and the stabilizing influence of the rotation–modified linear and nonlinear ion Landau damping.

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ANALYSIS OF THE PARTICLE DIFFUSION INDUCED BY STOCHASTIC FIELD FLUCTUATIONS USING THE FLUID APPROACH

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The fluid approach developed by Hirshman[1] and Shaing[2] to analyze neoclassical transport is used to describe diffusion of particles induced by small stochastic electric and magnetic fluctuations in a nonaxisymmetric toroidal field with well defined average magnetic surfaces. By using the two-lowest moment equations and assuming electrostatic fluctuations, equations for the average particle flow and the average density, as well as for the fluctuations of the particle flow and density around their averages values, are derived. Keeping only the lowest-order terms in the standard expansion, the first set of equations yields the well known ideal equations for the average of these quantities. The first order terms give the "radial" transport of particles in terms of the dissipation and the correlations of the particle flow and the density fluctuations with the field fluctuations. In order to obtain expressions for the "radial" particle flow in terms only of the field fluctuations, one should solve the set of equations for the fluctuations of the particle flow and density, in terms of the field fluctuations. A procedure to solve these equations is discussed.

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COMPARISON OF ATF AND TJ-II STELLARATOR EQUILIBRIA AS COMPUTED BY THE 3-D VMEC and PIES CODES

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The VMEC code[1] uses an energy minimization technique to determine the equilibrium properties of three-dimensional configurations. It is based on an 'inverse solver' technique in which a set of well behaved nested magnetic surfaces must be postulated to exist. It has been the principal tool for the determination of equilibrium configurations for the design of stellarators. The PIES code[2], on the other hand, determines the equilibrium configuration by direct integration along the field lines and can thus study systems with magnetic islands and multiple magnetic axes. This code has, until now, been used mainly for study of problems associated with tokamak configurations: investigations of the nonlinear saturation of tearing modes, the behavior of magnetic surfaces in the presence of error fields, etc.

It has long been recognized that comparisons of the calculations of the equilibrium properties of stellarators such as ATF, LHD, Wendelstein VII-AS, TJ-II, etc., by these two different approaches would be useful. Such calculations would provide additional validation for both codes and thus make additional tools available for the study of complex configurations. We have begun such a study for two devices: the ATF stellarator at Oak Ridge and the TJ-II heliac which is being built in Madrid. Preliminary studies indicate that the two codes are in good agreement. Detailed results from the calculations will be given.

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Theoretical Studies of Electron Absorption By Ion Cyclotron RF Fast Waves*

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A leading alternate method for central current drive in reactor grade plasmas involves the use of low frequency ion cyclotron RF (ICRF) fast waves at $f_0 < f_{C_T}$, where f_{C_T} is the tritium ion cyclotron frequency. The absorption mechanisms in this case are a combination of electron transit time magnetic pumping (TTMP) and electron Landau damping (ELD).

A toroidal full-wave ICRF code[1] was recently implemented at MIT which should provide an ideal tool for studying such ICRF current drive scenarios. This code is a finite element calculation which employs a spectral expansion of the electric field in poloidal Fourier modes. The code takes into account non-circular geometry of flux surfaces and includes the effect of the poloidal magnetic field. Variation in the parallel refractive index ($n_{||}$) of the injected ICRF waves can be properly treated with this model, thus providing accurate estimates of the parameter $\omega/k_{||}v_{te}$. Presently, the calculation of electron absorption in this code is being modified to properly account for the combined effects of electron TTMP and ELD. Results will be presented for proposed fast wave current drive experiments on DIII-D[2].

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Alpha Particle Detection by Fully Electromagnetic Thomson Scattering*

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We calculate the differential cross section for scattering incident gyrotron radiation in a warm, homogeneous magnetized plasma for parameters appropriate to TEXT, TFTR, and JET. Our model is derived from the linearized Vlasov-Maxwell equations by retaining electromagnetic field fluctuations in addition to the usual electron density fluctuations in an isothermal Maxwellian plasma. Alpha particles are modeled using the slowing-down distribution with a birth energy of 3.5 MeV and a drag velocity of 0.09 v_e. In the case of TEXT, we propose testing the diagnostic method by scattering off of fluctuations associated with energetic deuterium produced by neutral beam injection at 40 keV. We model this scenario with the appropriate beam and slowing-down distributions. Different cases are compared by plotting the ratio of scattered to incident power as a function of frequency, and we enforce the dispersion relation for the incident and scattered radiation (X- or O- mode) at every point. Cases for which the scattering is dominated by electromagnetic field fluctuations will be presented, and the role of the (electromagnetic) lower-hybrid resonance as an amplifier of the alpha particle signal will be made apparent.

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STEADY STATE D-T BURNING TOKAMAK.

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The requirements of a steady-state,D-T burning tokamak in terms of energy and particle confinement are outlined.For a plasma with central fuelling there is a net radial flow of electrons across each magnetic surface.Borrass and Pfirsch (IPP 6/155) have used plasma fluid equations to show that in such a case the instability responsible for the plasma transport must be manifest as an anomalous perpendicular resistivity Otherwise the poloidal flux is convected out leading to a steady-state skin current which would be hydromagnetically unstable.For an edge fuelled plasma the mean radial flow of electrons is zero.But there are then limitations on the beta value and severe requirements on the diffusion rates inwards and outwards of fuel ions and alpha particles respectively.

An experimental test of the physics involved requires current drive and a pulse length exceeding the skin-penetration time.However some deductions can be made from the results of present experiments and these will be presented.

Calculation of ideal MHD growth rate with compressibilty for three-dimensional stellarator plasmas

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We present first results of full 3-D calculations of ideal MHD growth rates with finite compressibility for stellarator plasmas. In previous studies [1], the incompressibility condition was assumed so that only stability index could be calculated. We have now incorporated the full compressional terms into the 3-D linear ideal MHD code TERPSICHORE [1]. The inclusion of this term has the advantage of being able to calculate the physical growth rate. The new code has been benchmarked against known stability results of 2-D axisymmetric Solov'ev equilibrium. We have also applied the code to truly 3-D stellarator equilibria and obtained physical growth rates. Preliminary results indicate it is essential to decouple sound waves from shear Alfvén waves in order to obtain accurate results. As a consequence, the number of Fourier modes needed to insure convergence is substantially broadened. Various numerical aspects of the new code will be discussed. Also a tunable integration finite element method [2] which has been implemented in the code will be discussed. This method has been shown to suppress numerically destabilized continuum modes near resonance sufaces induced by the hybrid finite element method. Detailed results will be shown. Finally, applications to the proposed LHD device will be presented.

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Particle and Energy Confinement Bifurcation in Tokamaks

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A bifurcation in the particle and energy confinement of a tokamak plasma is shown to follow from the assumptions (1) edge turbulence is suppressed by sheared $E \times B$ flow and (2) the radial ion pressure gradient is approximately balanced by the electric field. The particle and thermal diffusivities are assumed to be given by simple nonlinear functions of the radial electric field shear, which is related to the density and temperature gradients by the radial ion momentum equation, neglecting poloidal and toroidal flows. This study is complimentary to previous work (F.L. Hinton, to be published in Phys. Fluids B, March 1991) in which the radial electric field shear was related to the temperature gradient through the neoclassically-driven poloidal rotation. The particle source is given in terms of a simple expression for the neutral density, which is concentrated near the edge of the plasma. The density and temperature profiles have large gradient regions near the plasma edge when the heating power exceeds a threshold value. The particle and energy confinement times are significantly larger when this threshold is exceeded. The density gradient near the edge is larger than the temperature because the particle source is concentrated at the edge, while the heating is more uniformly distributed. Comparisons with experimental results for the L– to H–mode transition are given.

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Microscopic Theory and Simulation of Low-Frequency Plasma Motion

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Experiments on anomalous phenomena in magnetically confined plasmas provide evidence of complex plasma behavior involving low-frequency fluctuations, and necessitate fundamental knowledge of the latter. Comprehensive understanding of low-frequency kinetics is indeed a great challenge in both theory and simulation. With modern computers and numerical simulation techniques encompassing parallel computing, it is possible to study plasmas starting from basic physics models. This makes the fundamental theory especially important. Our report discusses the gyrokinetic description and its possible extension based on the Klimontovich equation as well as applications of full particle codes and gyrokinetic particle simulation. It is suggested that gyrokinetic particle code is more fluid-like, and may contain pseudo-kinetic effects.

SIMULATION STUDY OF MHD RELAXATION AND RECONNECTION PROCESSES IN RFP PLASMA

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We have studied several nonlinear processes in RFP plasma through the use of 3D MHD simulations. In particular, we have shed light on: 1) dynamo and self-sustainment in reversed-field pinch (RFP), 2) phase locking process in MHD relaxation, and 3) the heating and acceleration in magnetic reconnection process.

dynamo and self-sustainment in RFP: First, the contributions of the kink ($m = 1$) mode (linearly unstable) and of the $m = 0$ mode (driven by nonlinear coupling) to the dynamo are qualitatively evaluated using a high accuracy simulation. It is found that, if the free energy to drive kink instabilities is as small as that in the actual experimental plasma, the $m = 0$ modes, driven nonlinearly, play a more important role for the flux generation than the kink modes. Secondly, numerical simulations of the self-sustainment process in a RFP are performed. It is confirmed that the self-sustainment process is a coherent oscillating process composed of the MHD relaxation and the resistive diffusion processes. The excess magnetic energy, which appears as result of the resistive diffusion, is quickly released by the MHD relaxation process. As this process is repeated, the RFP configuration stays in the neighborhood of Taylor's minimum energy state. We find that the oscillation depends on the aspect ratio of the device and on the magnetic Reynolds number. These results agree with the nonlinear reconnection model for the $m = 1$ and 0 modes.

phase locking process in RFP: Toroidal phase locking process of kink modes is numerically observed in simulations of self-reversal and self-sustainment processes. It has characteristics similar to the 'slinky mode' observed in the OHTE experiment. A detailed investigation reveals that nonlinear coupling between the most unstable two kink modes governs the entire dynamics in all kink modes and leads to the phase locking process. These results suggest that the phase locking process is not a special phenomena of the RFP with a resistive shell, but is a general characteristic of MHD relaxation processes.

heating and acceleration in magnetic reconnection: We investigate the magnetic reconnection process as the heating and the acceleration mechanism of plasma. We find that reconnection can accelerate plasma over a local Alfven speed. This is a result of the fact that the magnetic field in the downstream area plays a similar role to *de Laval nozzle*. We also investigate the heating mechanisms in reconnection process. It is revealed that the viscous heating rate is as large as the joule heating rate in the reconnection process. This result implies that the viscous heating in the reconnection process is an important candidate for the mechanism to explain the RFP experiments where the ion temperature is higher than the electron temperature.

Waves in Electron Magnetohydrodynamics (EMH)*

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The EMH model is a simplification of MHD with the Hall effect, where the ions are taken to have infinite mass (they only provide the background charge) so that the momentum equation is dropped. The model was used to describe Z-pinches, the magnetic dynamo, and plasma opening switches.[1] Recently, exact solutions were given[2] showing rapid, collisionless, magnetic field penetration in pulsed power devices.

We interpret the rapid field penetration as caused by the presence of rapidly propagating (dispersive) waves, and have explored the waves present in the system. We find two possibilities: (i) For $\mathbf{k} \cdot \mathbf{B} \neq 0$, the phase velocity is proportional to $|\mathbf{k}|$ and is rapid for short wavelengths. (ii) For $\mathbf{k} \cdot \mathbf{B} = 0$, the phase velocity is homogeneous of degree zero in $\mathbf{k}$, slower than the previous case. Case (ii) shows, in fact, technical similarities to the ballooning mode phenomenon in MHD. Waves move rapidly along field lines (and more slowly across it) and set up a standing wave pattern if the field line is closed (as expected in plasma switches). However, we show that the standing wave does not grow in time so that there is no ballooning instability.

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Fast Axisymmetric Stability Calculations Using Variational Techniques

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A procedure for treating the axisymmetric ($n = 0$) stability of diverted plasmas in the presence of arbitrary, but toroidally symmetric, structures and active feedback circuits has been developed and implemented as a module in the TEQ free-boundary equilibrium code. This procedure is based on a variational solution of the ideal MHD normal mode equations. Inertia is ordered small but provides a constraint to allow the calculation of the poloidal and toroidal components of the plasma displacement. Feedback based on flux loop measurements is handled by introducing an adjoint system into the variational principle. Approximately 200 trial functions for the radial component of the plasma displacement and 200 magnetic surfaces are employed to obtain highly accurate estimates of the passive growth rate and the non-rigid eigenfunction. Nevertheless, the method is extremely fast: typically 10–20 sec of Cray 2 CPU time are required to analyze a realistic tokamak configuration. This speed, along with the direct coupling to the MHD equilibrium solver, allows interactive investigations of tokamak axisymmetric stability. Benchmarks with TSC and GATO will be presented along with parameter scans for ITER and BPX. The results emphasize the importance of considering non-rigid mode effects which for ITER, yield higher nominal growth rates (non-rigid: 45 Hz, rigid: 25 Hz) and atypical internal inductance dependence (smaller l_i more unstable).

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Nonlinear magnetohydrodynamics by Galerkin-method computation

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A fully spectral numerical code based on a Galerkin approximation method is used to explore the properties of voltage-driven dissipative magnetofluids embedded in an externally-maintained dc magnetic field inside a periodic cylinder with circular cross-section. The trial functions are orthonormal eigenfunctions of the curl (Chandrasekhar-Kendall functions). At a threshold of the pinch ratio predicted by linear instability analysis and minimum-energy-dissipation-rate theory,[1,2] a transition is observed from axisymmetric resistive equilibria without flow to a helically-deformed, two-dimensional laminar state with flow. This threshold of the pinch ratio is a function of the aspect ratio and the Hartmann number only, and corresponds the boundaries of possible axisymmetric behavior of both the tokamak and the reversed-field pinch. A second transition between the first helical state and a multi-mode stationary state occurs at a higher critical value of the pinch ratio. States of minimum energy dissipation rate seem to be preferred. At high values of the pinch ratio, fully-developed magnetohydrodynamic turbulence is observed.

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The Force on a Plasma due to an Electromagnetic Wave

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The interaction of electromagnetic waves with a plasma is derived in the geometric optics approximation. In particular, the force exerted on the plasma is determined by the plasma conductivity tensor, $\boldsymbol{\sigma}$. The current in the plasma that is induced by the wave is written in four notation, $j_w{}^{\mu}(x)=\int\alpha^{\mu\nu}(x+s/2,k)A_{\nu}(x+s)\exp(iks)\,d^4s d^4k/(2\pi)^4$. The total four-current j^{μ} is the sum of the current induced by the wave and the current in external sources, such as antennas $j_x{}^{\mu}$. The external currents $j_x{}^{\mu}$ are related to the four-potential A_{ν} by the tensor $\beta^{\mu\nu}$. The tensors $\alpha^{\mu\nu}$ and $\beta^{\mu\nu}$ obey the constraints $k_{\mu}\alpha^{\mu\nu}=0$ from $\partial_{\mu}j_w{}^{\mu}=0$ and $\alpha^{\mu\nu}k_{\nu}=0$ from gauge invariance. In the radiation gauge, $E=-(\partial A/\partial t)/c$, one needs only the three-tensor $\boldsymbol{\alpha}$, which is closely related to the plasma conductivity, $\boldsymbol{\alpha}=i\omega\boldsymbol{\sigma}/c$ and the three tensor $\boldsymbol{\beta}=-(c/4\pi)[\mathbf{kk}-(\mathbf{k}\cdot\mathbf{k})\mathbb{I}+(\omega/c)^2\mathbb{I}]-\boldsymbol{\alpha}$. The three polarizations of waves $\omega(\mathbf{k},\mathbf{x},t)$ are given by the vanishing of one of the eigenvalues β of $\boldsymbol{\beta}_h$, the Hermitian part of $\boldsymbol{\beta}$, and the eigenvectors give the polarizations of E. A direct calculation of the force on the plasma is made using the Wigner tensor $4\mathrm{J}_{\mu\nu}(x,k)\equiv\int A_{\mu}(x-s/2)^{*}A_{\nu}(x+s/2)\exp(iks)d^4s/(2\pi)^4$. The wave action $J=\int[\mathrm{J}_{\mu\nu}\partial(\beta^{\mu\nu})/\partial\omega]d\omega$ obeys $\partial J/\partial t-(\partial\omega/\partial x)\cdot(\partial J/\partial k)+(\partial\omega/\partial\mathbf{k})\cdot(\partial J/\partial\mathbf{x})=-\nu J$ with $\nu\equiv-2i\beta_a/(\partial\beta/\partial\omega)$ the damping rate and β_a the anti-Hermitian part of $\boldsymbol{\beta}$ dotted with the polarization vectors. The momentum and energy of the wave relative to external sources are $\int\mathbf{k}Jd^3k$ and $\int\omega Jd^3k$. The three-force on the plasma is

$$f_i=\int[k_i\nu+(\partial\alpha/\partial x_i)/(\partial\beta/\partial\omega)]Jd^3k-\partial\{\int k_i[(\partial\alpha/\partial\omega)/(\partial\beta/\partial\omega)]Jd^3k\}/\partial t$$
$$-\partial\{\int[(\alpha\delta_{ij}-k_i\,\partial\alpha/\partial k_j)/(\partial\beta/\partial\omega)]Jd^3k\}/\partial x_j.$$

with α the Hermitian part of $\boldsymbol{\alpha}$ dotted with polarization vectors. For example, the force exerted by the Alfvén and fast waves are $f=-\nabla\cdot\mathbb{p}$ with $\mathbb{p}=\int(2\hat{\mathbf{k}}\hat{\mathbf{k}}-\mathbb{I})\omega Jd^3k/2$ and $\hat{\mathbf{k}}$ the direction of the wavevector. Work supported by the US Department of Energy grant DE-AC02-76CH03073.

2D-HYBRID PARTICLE MODEL WITH NON-LINEAR ELECTRON DISTRIBUTION

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ABSTRACT

A 2D, hybrid (particle-ion, fluid-electron) simulation code characterized by the solution of the non-linear modified Poisson equation, which results assuming the Boltzmann distribution for the electrons, is presented.
Following [1], the field solution is achieved through an iterative procedure. Anyhow a new scheme is considered. The potential is not obtained by directly solving the finite difference equation but via the Green's function method.
The procedure begins with the first guess for the potential. This is found through the solution of the linearized modified Poisson equation. The Green's function for this equation, in the 2D case which is considered, can be found analytically in term of the Neumann functions [2], [3].
Once the potential corresponding to the linearized modified Poisson equation is known, the first approximation of the electron (Boltzmann) distribution can be calculated. This distribution, plus the one given by the (particle) ions, is considered as the source term for the Poisson equation (which now is not "modified" since the fluid electron component is taken into account in the source term itself).
The solution of this Poisson equation gives the second approximation of the electric potential and is still obtained via the Green's function method (as it comes from the Coulomb law, modified for the 2D case, [2]).
Each time step this procedure can be iterated according to the desired accuracy. The last iteration cycle is different: in fact the direct solution for the electric field can be obtained, without numerical differencing from the potential. It is sufficient in this case to consider the electric field Green's functions (x- and y-component) for the Poisson equation (in place of the electric potential Green's function).
The first results obtained with this new code are here presented and compared with previous simulation runs based on a linearized Boltzmann distribution model, as in [2], [3].

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3–D Hybrid Kinetic/MHD Simulation for the Energetic Particle Effects*

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The 3-D nonlinear toroidal MHD code, *MH3D*,[1] has been modified to include the gyrokinetic effects of the energetic particles. This *MH3D-K* code treats fast non-thermal ('hot') ions as particles which contribute to the pressure tensor:

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p_b - \nabla \cdot \mathsf{P}_h + \mathbf{J} \times \mathbf{B},$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} = \nabla \times (\mathbf{v} \times \mathbf{B}),$$

where the subscript b (h) represents the bulk fluids (hot component), and the combined bulk and hot component moments are represented as nonsubscript variables. The pressure tensor P_h is obtained from the particle contribution using **B** and **E** given by the MHD part.

The above scheme can be called a pressure coupling in the combined momentum equation. Alternatively, the bulk fluid momentum equation can be used with current coupling (instead of the pressure) to produce a similar system:

$$\rho_b \frac{d\mathbf{v}_b}{dt} = -\nabla p_b + \mathbf{J}_b \times \mathbf{B} = -\nabla p_b + (\nabla \times \mathbf{B} - \mathbf{J}_h) \times \mathbf{B},$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} = \nabla \times (\mathbf{v} \times \mathbf{B}),$$

where $\mathbf{J}_h$ is obtained from the particle contribution.

It can be shown that the above two systems can be equivalent in some parameter regime. The existence of these two equivalent systems is useful in debugging the code and understanding the underlying physics.

The *MH3D-K* code will be used to study the nonlinear behavior of the energetic particle effects, such as the energetic particle stabilization of sawteeth and ballooning modes, the fishbone oscillations, and alpha driven TAE modes.

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Radiative Instability in a Diverted plasma

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Bifurcations between thermal equilibria are well known to occur for a radiating plasma at a constant pressure profile[1]. For sufficiently high impurity concentrations (typically 5 % for oxygen) three steady state solutions of the heat equation are found. The lowest temperature state is always stable (radiation condensation instability) when the radiation loss is a function of temperature only. Surprisingly,this result holds even if this function strongly decreases with the temperature. In the present study we consider the important case where the ratio of impurity and electron density and thereby the radiation loss, depends explicitly on space. A general stability criteria is demonstrated. We prove that two types of radiation limits can affect the layer. One of these limits corresponds to a lack of equilibrium, while the other one is a stability loss, associated with the onset of a temperature perturbation , leading to a transition of the plasma state towards another stable equilibrium. This last limit depends strongly on the impurity profile. For two configurations of interest, i.e. the axisymmetric and ergodic divertors, the stability relatively to the thermal condensation of a cold dense and radiating layer is discussed in term of impurity density and plasma power outflux.

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Bootstrap Equilibria in Tokamaks

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Recent experiments on TFTR have shown clear indications of the presence of large bootstrap currents which, in some cases, constitute the predominant component of the plasma current / 1,2 /. Bootstrap equilibria / 3, 4 /, sustained by neutral beam injection, appear possible, and we seek to investigate their main qualitative features by analytical and computational studies of some simple one-dimensional models. In the large-aspect-ratio limit, the neoclassical steady-state equations in the banana regime reduce to a system of first-order nonlinear odinary differential equations for n, T_e , T_i, and I. This system was studied in Ref. 4 numerically in the case of no mass source, no induced electric field and $T_e = T_i$. We have found for this case a first integral for the nonlinear equations; this integral allows us to compute analytically the total plasma current and, in some cases, the equilibrium profiles. However, for relevant plasma parameters, the analysis yields reasonable estimates for the total bootstrap current, but unrealistic temperature profiles. To improve the model we have replaced the neoclassical heat flux with various forms for the anomalous heat flux and solved the corresponding equations numerically. Preliminary results of these numerical investigations are presented. Possible MHD activity in these bootstrap equilibria, as well as the effect of such activity on the sustenance of these equilibria will be discussed.

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Fluid Model for Bounce-Averaged Trapped Electrons*

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Trapped electrons play a key role in driving collisionless drift-wave instabilities. Their linear response function is characterized by a spread in magnetic drift velocities, formally similar to the spread in parallel velocities in the case of linear Landau damping. We follow the method of our Landau damping model[1] to develop moment equations which model linear bounce-averaged trapped electron response and introduce nonlinearity via the replacement $\partial/\partial t \rightarrow \partial/\partial t + (\mathbf{E}\times\mathbf{B}c/B^2)\cdot\nabla$.

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Resistive MHD Studies of TFTR Discharges

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MHD instabilities, thought to be resistive in character, are frequently observed in the 'supershot' operating regime of TFTR ($\varepsilon\beta_p \leq 0.7$). These instabilities are always accompanied by substantial degradation of the confinement. Similarly of interest are recent experiments[1] at much larger β_p ($\varepsilon\beta_p \leq 1.6$), achieved through ramping the current during the beam heating phase of the discharge. In this latter regime the confinement can exceed three times the corresponding L-mode value and the β value normalized to I/aB can be as large as 4.7. Representative discharges from each of these operating regimes have been analyzed using a linear resistive MHD stability code with equilibrium pressure and q profiles obtained initially from the TRANSP analysis code. The main difference between the two types of discharge, as far as stability is concerned, is shown to be the shape of the current density profile. The sensitivity to the assumed parameters will be discussed.

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Tokamak Magnetic Islands in the Presence of Nonaxisymmetric Perturbations*

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The effects of a small, externally imposed, nonaxisymmetric magnetic field perturbation on magnetic islands are studied analytically, assuming zero beta, tokamak ordering, and narrow islands. For the tearing stable case, the conditions under which the self-consistent plasma response is self-healing or amplifying are elucidated. For the tearing unstable case, the quasilinear theory of tearing modes is extended to a description of locked modes. We give explicit locked mode solutions for a slab model.

We compare our analytic solutions to toroidal, three-dimensional numerical solutions. We also discuss the implications for construction tolerances in BPX.

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SPATIO-TEMPORAL CHAOS IN THE SATURATION OF AN UNSTABLE WAVEPACKET*

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ABSTRACT

The term spatio-temporal chaos is used to describe a spatially extended system where coherent structures or spatial patterns exhibit chaotic dynamics. This is to be contrasted with fully developed turbulence where there is a cascade to finer and finer scales. We have found such spatio-temporal chaos to exist in the space-time evolutions of the nonlinear coupling of three coherent wavepackets describing the saturation of a high-frequency unstable wave by coupling to two damped waves at lower frequencies. We report on the results of the case where the unstable wave group velocity is in between the group velocities of the other two damped waves.

In its conservative form (with no growth or damping) the space-time evolution of this nonlinear interaction is integrable by inverse scattering and exhibits the generation and interchange of solitons by the three wavepackets [1,2]. With growth and damping we find that the unstable wavepacket cascades to short wavelengths by emitting solitons in the other two wavepackets. The large-system long-time behavior of the nonlinear coupling is characterized by coherent structures that interact chaotically; the coherent structures are remnants of solitons. We refer to these objects as quasi-solitons. They are of finite spatial extent but they damp as they propagate and they do not preserve their form after collisions as solitons would. For space-time scales larger than those that characterize these structures there is no coherence.

We do not find routes to chaos traditionally ascribed to low dimensional systems as, for example, in this nonlinear three-wave interaction in time only (i.e. with imposed spatially constant amplitudes) [3,4]. We find that spatio-temporal chaos can occur for arbitrarily small growths of the high-frequency wave. All that is required is that the system size be large enough to accommodate more than one quasi-soliton.

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PARTICLE TRANSPORT AND ROTATION DAMPING DUE TO STOCHASTIC FIELD LINES

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In a tokamak with stochastic field lines, there is a contribution to particle transport due to sound wave propagation along the field lines. This diffusion is *not* intrinsically ambipolar ($e\nabla_{||}\phi - \nabla_{||}p_e/n = 0$) if the perturbed magnetic fields are global and therefore this effect can short out the electrostatic potential associated with plasma rotation. This is of potential importance because of the possibility that asymmetric transport can generate rotation, which in turn can suppress the turbulence.[1] Quasilinear theory predicts a diffusion coefficient $D \sim C_s\ell_c(\delta B/B)^2$ for this process, which leads to rotation damping. The effects of viscosity, Landau damping, and toroidal curvature will be discussed.

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Resistive MHD in Tokamak Edge Regions*

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Several Results on resistive MHD in tokamak edge regions, relevant to the H-mode transition, are presented: quasilinear drift tearing modes as an H-mode trigger; stabilization of drift tearing modes by sheared poloidal rotation; and the effect of sheared rotation on electrostatic drift resistive ballooning modes.

Quasilinear drift tearing modes have a critical $\Delta' \sim T_e^3/B_T^2$, which might give a threshold similar to the observed scaling. The quasilinear regime is valid for island widths as large as the tearing layer width, which can be about 1-3 cm, for typical edge parameters. Cross field thermal conductivity has an essential role in maintaining quasilinear islands. Stabilization of the modes might trigger the H-mode, if destruction of magnetic surfaces around the separatrix increases edge transport, and shorts out a radial electric field. Because drift effects do not persist in the nonlinear regime, drift stabilization does not work for larger islands.

Sheared rotation is an effective stabilization mechanism in both quasilinear and nonlinear regimes of the drift tearing mode. In the quasilinear regime, velocity shear increases the critical Δ'. The required velocity gradient to stabilize a nonlinear island is large, but experimental parameters appear adequate to provide stabilization.

Sheared rotation also has a stabilizing effect on electrostatic resistive ballooning modes. Only the drift resistive ballooning mode survives above a critical edge T_e. The linear growth rate of these modes is slowed by sheared rotation, when the poloidal velocity gradient exceeds the drift frequency. A resonance can occur when $v_\theta' = \omega_*$, giving a growth rate proportional to $\eta^{1/2}$. For shorter wavelengths, the growth rate is not affected by the rotation.

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Fueling Effects on Drift Wave Turbulence

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We consider two cases of fueling effects on drift wave turbulence: an impurity gradient and an ionization source. In the region of neutral penetration near the edge, particle sources from ionization can couple to collisional drift waves to produce ionization-driven drift wave turbulence (IDDWT). In addition, large parallel shear flows due to charge-exchange are considered. A two-field model coupling density and parallel ion flow perturbations is developed. In the nonlinear theory, it is found that the "$E \times B$" nonlinearity dominates the polarization nonlinearity, producing nonlinear damping via mode coupling to small scales in the density equation and a shear viscosity (via Compton scattering) in the parallel flow equation. Due to the stabilizing effect of the electron temperature gradient, an inward particle flux is predicted, and occurs more generally than the inward flux driven by the ion-mixing mode.[1] Since the ionization instability is linearly proportional to the neutral density, we suggest IDDWT as a mechanism for inward flow during neutral gas puffing. A model for impurity gradient driven turbulence is developed and discussed. The coupling of ion and impurity dynamics produces an instability driven by the free energy in the impurity density gradient.[2] We consider impurity modes in the drift wave range, $\omega \sim \omega_*$. A saturation calculation is performed and scalings for ion and impurity density fluctuation levels are determined.

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STOCHASTIC DIFFUSION IN TWO-DIMENSIONAL PERIODIC FLOWS

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Abstract

The global effective diffusion coefficient D^* for a two-dimensional system of convective rolls with a time dependent perturbation added, is calculated numerically. The perturbation produces a background diffusion coefficient D, which is calculated analytically using the Menlikov-Arnold integral. This intrinsic diffusion coefficient is then enhanced by the unperturbed flow, to produce the global effective diffusion coefficient D^*, which we can calculate theoretically for a certain range of parameters. A scaling law derived using percollation theory[1] is also compared to the numerical results.

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TWO DIMENSIONAL MODELING OF LOOP AND FOLDED WAVEGUIDE ICRF ANTENNAS*

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In order to provide a rational basis for evaluation of BPX antenna designs, we have used the Oak Ridge recessed antenna modeling code RANT to perform extensive calculations for a number of different BPX antenna designs (hybrid, port mount designs, wall mount designs) for a variety of edge density profiles. The magnetic field is constant and oriented in the z direction. The boundary consists of a perfectly conducting wall with an arbitrary number of recesses (2 recesses for these calculations). Each recess contains a y-directed current strap (zero thickness in x) of width W_s in z. The plasma, current straps and boundary are uniform in y (i.e. there is no poloidal variation). The model therefore gives loading per unit length of current strap. The plasma is uniform in z and has arbitrary variation in R (or x) out to $R = R_{\text{edge}}$ beyond which the density vanishes. One can visualize this as the location of a Faraday shield or antenna bumper limiter which cuts off the plasma. The x variation of the density profile is arbitrary. The field and the z distribution of antenna current $J_y(z)$ is expanded in terms of the appropriate eigenfunctions for each region.

The folded waveguide concept provides an alternative to the traditional strap design for launching ICRF power into a plasma. By exciting a mode in the waveguide and placing metal straps across alternating openings on the plasma side, a magnetic field pattern is generated with characteristics similar to a strap antenna. This mode has a voltage minimum on the plasma side of the waveguide. The field patterns are calculated using a discrete set of current elements that are adjusted to approximately satisfy the boundary conditions for the excited waveguide mode. The calculated fields are also in reasonable agreement with experimental vacuum magnetic field measurements. Three dimensional results for the fields and power radiated into a cold plasma from the equivalent current set will be presented. Comparisons will be made to a single strap antenna.

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

Simulation of Divertor Biasing and Cross-Field Drifts using the B2 Edge-Plasma Code *

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We have included the effects of parallel current, divertor plate biasing, and cross-field drifts in the two-dimensional fluid code B2.[1] We report on simulations of biasing for the single null DIII-D configuration. The density and temperature at the edge of the plasma core are set at $n_e = 2 \times 10^{19}$ m^{-3} and $T_e = T_i = 100$ eV. The divertor plate is biased over the range -50 V to +50 V, during which the ratio of the power on the outer plate to that on the inner plate varies from 0.27 at -50 V to 4.5 at +50 V, while the total power remains near the 1 MW level. For zero bias, the power ratio is 2.6; this asymmetry is caused by toroidal geometry effects. The dominant mechanism which gives rise to the control over the power asymmetry is the convection of electron energy in the poloidal direction by the electron drift along the magnetic field in response to the changed potential. We shall discuss some scaling with parameters and the effect of different Z_{eff}.

We have included cross-field drifts caused by gradients of pressure, temperature, and potential perpendicular to the magnetic field. Such drifts give rise to asymmetries even for double null divertor configurations. The electric field is calculated on the open magnetic field lines but is yet to be done for the core region.

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1 B. J. Braams, NET Report Nr. 68, January, 1987

Fluid Model Description of Tokamak Edge Turbulence*

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Experimental results on TEXT and ATF indicate that electrostatic fluctuations can explain the edge transport of particles and energy. Certain mechanisms for drive (impurity radiation, ionization, as well as density and temperature gradients) and stabilization (poloidal velocity shear) are suggested by these results.

A comprehensive nonlinear model of the turbulence at the edge of TEXT is being developed. It includes the coupling of the plasma dynamics, described by the nonlinear reduced Braginskii equations with diamagnetic effects, to impurity radiation, ionization sources and a charge exchange sink at the edge. Impurity radiation gives rise to radiation-driven drift thermal instability turbulence on the core side of the velocity shear layer. In the outer region, the ionization drive dominates and excites instabilities in several ways. The most direct is through the particle source from the neutrals, which couples to, and destabilizes, the collisional drift waves. Ionization also contributes to the drift thermalinstability through the energy sink, but this drive is weak. Together with the charge-exchange momentum sink, ionizationcan significantly modify the momentum balance and cause a gradient in the parallel velocity. This parallel velocity gradient can increase the instability.

All of these effects are presently being incorporated in our model and the results of linear and nonlinear calculations, as well as their comparisonswith TEXT and ATF experimental results, will be reported.

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

NON-LOCAL EFFECTS OF ALPHA PARTICLES ON SECOND-HARMONIC ICRF HEATING

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A model based on the linearized Vlasov-Maxwell equations, taking into account the non-local interactions of particles due to their finite Larmor radii, has been developed. Assuming an inhomogeneous 1-D slab plasma, Maxwellian equilibrium distribution functions and k_y=0, it leads to a system of one first-order and two second-order integro-differential equations for E_x and E_y, E_z respectively. These equations are valid for arbitrary value of $k_\perp\rho_\sigma$, where $k_\perp$ is the perpendicular wavenumber and ρ_σ the Larmor radius of species σ. Therefore, the code SEMAL, solving these equations, can be used to study the effects of alpha particles on the ion cyclotron range of frequency (ICRF) heating. These effects are shown to be much less significant for heating at the second-harmonic of deuterium than expected from local models. Other heating scenarii as well as the influence of k_z, T_α and n_α/n_e are also investigated. The results indicate under which conditions the power absorption by alpha particles start to dominate and, therefore, degrade the heating efficiency.

2D17

DRIFT RESISTIVE BALLOONING MODES AND EDGE FLUCTUATIONS

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The drift resistive ballooning modes are good candidates for edge fluctuations in tokamaks. Using the ballooning mode formalism, the study of these modes involves three second order coupled differential equations for density, vorticity and temperature. These equations have been solved numerically for edge parameters for TEXT and D-III D. The long wavelength cut off is caused by the stabilizing influence of η_e where $\eta_e = d\ell_n T_e / d\ell nn$ or acoustic induced shear damping and occurs for mode numbers $m \simeq 40 - 50$. For TEXT, the magnetic fluctuations are negligible and the modes are electrostatic with potential fluctuations larger than the density fluctuations. For D-III D, the modes are electromagnetic in character. The good agreement with observed features on both TEXT and D-III D make the drift resistive ballooning mode an attractive candidate for edge fluctuations and transport.

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Scattering and Localizability of ECH Power in BPX*

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Drift-wave density fluctuations that are present in all tokamaks scatter injected RF power used for electron-cyclotron heating (ECH). The resultant broadening of the microwave beam degrades the localizability of power deposition, raising power requirements for, or even preventing, stabilization (by heating near the $q = 1$ or $q = 2$ surfaces) of sawteeth or tearing modes. This paper reassesses scattering and localizability for new parameters of the Burning Plasma Experiment (BPX). Our reassessment uses a quasilinear approach to estimate the scattering. That approach differs from the one used in previous work[1,2,3] and is appropriate because BPX has a small ratio of RF wavelength to density-fluctuation wavelength. We treat ordinary-mode microwave beams propagating nearly perpendicular to a realistic equilibrium magnetic field. Electron-cyclotron absorption is calculated in the weakly relativistic approximation.[4] We find that scattering broadens the beam mostly in the poloidal direction and is neither negligible nor seriously large. For local heating near $q = 2$, better localizability and better accessibility to outer flux surfaces is achieved by using a mirror to reflect the beam within the poloidal rather than the equatorial plane.

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

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Analytic and Computational Studies of Inertial-Electrostatic Confinement*

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We are embarking on a comprehensive study of inertial-electrostatic (IEC) confinement. Experimental work complemented and guided by theoretical analysis will be pursued. The experimental effort will be centered at the University of Illinois and utilize spherical devices that can be operated in three possible modes: a) ion injection, b) ion production by ionization of background gas with thermionically emitted electrons, and c) ions produced by glow discharge.

Experimental diagnostics will glean data to determine the spatial dependence of both the neutron-emission source and the associated electrostatic potential. This data will be used to assess and improve our physical understanding of the IEC concept. We propose to utilize the analytical and computational strengths of the Los Alamos National Laboratory to achieve this mission. A new PIC code is being developed to study electrostatic confinement devices as well as Tokamaks. The code is three-dimensional and is based on the implicit moments approach of Mason, Forslund and Brackbill. It is pseudospectral in two dimensions and has a staggered mesh in the third dimension, which allows one to forgo solving Poisson's equation directly.

At present, the code only contains the two fluid equations. Tests of resonant light waves and plasma waves will be presented. Applications to electrostatic confinement problems will be discussed.

* This work supported by LANL

Stochastic Losses of Alpha Particles in Tokamak*

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We solve the Fokker-Planck equation for alphas in a tokamak including both pitch-angle scattering and slowing down. Losses of toroidally-trapped alphas due to the stochastic diffusion related to ripple are accounted for by assuming that all the stochastic particles immediately leave the device. This assumption permits us to solve the problem with proper velocity-space boundary conditions for the distribution function. This generalizes the approach of J.G.Cordey[1] and C.T.Hsu *et al.*[2] The eigenfunctions are found numerically.

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Numerical Simulation of Drift Wave Turbulence in Fluid Models with Landau Damping

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Following the work of Hammett and Perkins [1], we construct a nonlinear electrostatic fluid-like model for collisionless circulating ions and electrons containing Landau damping. Six-field perturbations (density, electric potential, ion and electron parallel velocity, and ion and electron pressure) are advanced in time. Both density and temperature gradients are considered. Polarization drift as well as FLR effects are included and the system may be generalized to include curvature effects. Apart from artificial viscosity at large perpendicular wave numbers, the only dissipative element is a collisionless parallel heat diffusivity ($V_{\rm th}/k_{\parallel}$) for both ions and electrons. (There is no parallel viscosity.) This corresponds to a three-pole approximation of the plasma dispersion (Z-) function [1]. A similar six-field set set can be written for hydrogen and impurity ions with Boltzmann electrons. The equations of motion are encoded in an (m, n, r) representation with a sheared and curved magnetic field [2]. There are several motivations for treating such complex systems. In addition to the ion temperature gradient mode, the electron-ion set contains the universal drift mode which may have nonlinear instability properties similar to the collisional drift wave [3]. Both sets contain mass ratios ($Am_{\rm i}/m_{\rm e}$ or $Am_{\rm i}/m_{\rm I}$, respectively) which may be a key to the mysterious atomic number (A-) scaling in tokamak confinement. Preliminary studies of linear stability of the models in comparison to the true kinetic response will be discussed and some initial single helicity nonlinear simulations will be presented.

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*NERSC at Lawrence Livermore National Laboratory, Livermore, California.

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A SELF-CONSISTENT MODEL FOR CARBON PELLET-PLASMA INTERACTION

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It is important to understand the interaction of low-Z pellets with fusion plasmas because of the potential use of pellets for (i) plasma refueling, (ii) current density and local magnetic field diagnostic, as well as (iii) an alpha-particle diagnostic. Parks et. al.[1] have introduced a phenomenological model for the injection of low-Z pellets into a hot plasma by extending the neutral gas shielding model that has been successfully used in the study of hydrogen pellets[2]. By using thermodynamic arguments and other assumptions, Parks et. al.[1] determine the ablation cloud parameters by coupling the electron heat flux at the sonic and pellet surface. Here, we examine some of the major assumptions made in this model[1] - which are

(1) the subsonic ablation cloud density near the pellet surface has a radial power law decay $r^{-\alpha}$, where $5 < \alpha < 6$,

(2) the sonic radius to the pellet radius, $r_*/r_p \approx 1.33$

(3) the ablation cloud temperature at the pellet surface $T_p \approx 0.6$ eV

(4) the ablation cloud Mach number at the pellet surface, $M_p \approx 0.5$

(5) local thermodynamic equilibrium (LTE) prevails throughout.

We employ an eigenvalue shooting code to determine self-consistently the location of the pellet surface. The boundary conditions at the carbon pellet surface are much different from that of a hydrogen pellet due to the much larger sublimation energy needed to vaporize the carbon pellet. In particular we find a somewhat slower radial decay of the ablation cloud density as well as a significant departure from LTE conditions in regions where C3+ and higher ionized states are found under reactor-like conditions. These regions are important since an alpha particle diagnostic will utilize double charge exchange. We also examine the effects of these differences on the conclusions of Parks et. al.[1] as well as the sensitivity of their model to parameter changes.

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MFE2
A General-Purpose 2D Moving Finite Element Code for Nonlinear, Time-Dependent Fluid Problems

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A new code has been developed to apply the method of Moving Finite Elements (MFE) to a general class of nonlinear, time-dependent fluid problems of the form

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot \mathbf{F} = \mathbf{S},$$

where $\mathbf{u}$ is an n-vector of unknowns, $\mathbf{F}$ and $\mathbf{S}$ are corresponding vectors of fluxes and sources, t is the time, and the 2D vector $\mathbf{x}$ of independent spatial variables may be expressed in arbitrary curvilinear coordinates. Components of $\mathbf{u}$ may be, for example, density, chemical concentrations, temperatures, and components of velocities and electromagnetic fields. The general forms of the fluxes and sources are given by

$$\mathbf{F} = \mathbf{C}(t, \mathbf{x}, \mathbf{u}) - \mathbf{D}(t, \mathbf{x}, \mathbf{u}) \cdot \nabla \mathbf{u}, \qquad \mathbf{S} = \mathbf{S}(t, \mathbf{x}, \mathbf{u}, \nabla \mathbf{u}),$$

where $\mathbf{C}$ represents convective terms, $\mathbf{D}$ is a diffusion tensor, and $\mathbf{C}$, $\mathbf{D}$ and $\mathbf{S}$ may be arbitrary nonlinear functions of their arguments. An equally general formulation of boundary conditions is incorporated into the code.

MFE is a form of Galerkin method using linear finite elements on a moving grid which adapts dynamically to the evolving solution, packing finely in regions of rapid variation and loosely elsewhere. PDEs are expressed in variational form. The grid is composed of triangles, which are dynamically deformed by the method, and may be arbitrarily structured and infrequently reconnected. Simultaneous minimization with respect to time-dependent amplitudes and node positions generates a coupled system of ODEs for advancing these quantities in time. The ODEs are solved by a stiffly stable method which eliminates CFL stability constraints on the time step. The use of large time steps is greatly facilitated by the smooth motion of the grid and solution together which is inherent in the method. Gradient weighting of the variational is used to greatly improve the motion of the nodes, allowing them to concentrate where they are needed to resolve the solution.

This method is well suited to the solution of some of the most challenging fluid problems, characterized by strong moving shocks, thin boundary layers, anisotropy, multiple time scales, and chemical reactions. Such problems are difficult or impossible to treat using more conventional methods. Since the plasmas encountered in Magnetic Fusion Energy (MFE) are commonly plagued by these problems, there are many applications of MFE to MFE, and this method could make an important contribution to the Numerical Tokamak project currently under discussion.

Applications of the code to a number of physically interesting problems will be presented. These will be illustrated with 3D graphics developed for this purpose, using the Silicon Graphics GL library.

Moment Expansions and the Neoclassical Approximation for a Model Kinetic Equation*

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Abstract

A simple, model kinetic equation proposed by D. Pfirsch is solved by moment expansions techniques and the results are examined for convergence and compared with the neoclassical approximate solution. The model equation

$$v\,\frac{\partial f}{\partial x} + E\sin x\,\frac{\partial f}{\partial v} = \nu\,\frac{\partial}{\partial v}\left\{\frac{\partial f}{\partial v} + (v - u_d)f\right\}$$

involves the three parameters ν, where $1/\nu$ is the collisionality of the system, u_d is the mean velocity to which the system is driven, and E, the perturbing potential. The domain of interest is one in which E, u_d, and ν are all small. Limitations and domains of utility of various approximations are compared with the numerical results. It is clear that the origin in (E, u_d, ν) space is a highly singular point, and properties of the solution near the origin depend on the path of approach to the origin.

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Weakly Nonlinear Theory of Multiple-Helicity Resistive Interchange Modes

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Resistive interchange modes are linearly unstable in the peripheral region of sterallator/heliotron plasmas which have a magnetic hill there and therefore they are candidates for the cause of the edge turbulence and the resultant anomalous transport. Here nonlinear behavior of resistive interchange modes near marginally stable states is theoretically studied under the multiple-helicity condition. Reduced fluid equations in the sheared slab configuration are used in order to treat a local transport problem. With the use of the invariance property of local reduced fluid model equations under a certain transformation of the multiple-helicity modes, a weakly nonlinear theory for single-helicity modes by Hamaguchi and Nakajima [1–3] is extended to the multiple-helicity case and applied to the resistive interchange modes. We derive the nonlinear amplitude equations of the multiple-helicity modes, from which the convective transport in the saturated state is obtained. It is shown how the convective transport is enhanced by nonlinear interaction between modes with different rational surfaces compared with the single-helicity case. We confirm that theoretical results are in good agreement with direct numerical simulations.

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Properties of c/ω_{pe} Filaments*

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Recent experimental and modelling studies by R.J. Taylor strongly suggest that filamentary structures having radial dimension on the order of the electron skin depth, c/ω_{pe}, play an important role in the CCT device, and possibly in major tokamaks. The present analytical and numerical study explores some of the fundamental properties of these structures with the aim of developing a self-consistent picture of energy transport and fast ion generation. One of the topics investigated concerns the space-time evolution of pulses excited by a perturbation across the confining magnetic field, as may result from conductivity modulations[1] or antennas. The distortion of the pulses due to finite ion Larmor radius is considered and the possible role of α particles is examined. The interaction of the pulses with various plasma modes is under investigation.

*Work Sponsored by USDOE

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2D27

Nonlinear Dynamics of the Toroidal Alfvén Gap Mode Driven by the Diffusing Alpha Particles

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We investigate an effect of alpha particle anomalous transport on the evolution of a linearly unstable toroidal Alfvén gap mode. A three dimensional guiding center code is used to analyze the diffusion of alpha particles induced by the gap mode of a given mode structure and to calculate the particle-to-wave nonlinear power transfer as a function of mode amplitude. We then employ energy balance to describe the time evolution of the mode amplitude. In addition to mode pumping by alpha particles, dissipation of the mode due to Landau damping on plasma electrons is taken into account. The balance between these two effects can determine the saturation amplitude.

Nonlinear Dynamic Models Displaying Temporal Features of Sawtooth Oscillations

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Abstract

There is at present no completely satisfactory theory of sawteeth in tokamaks. Although the simulations of Denton et al (Phys. Rev. Letts. **56**, 2477, 1986) and Aydemir et al (Phys. Fluids **B**1, 744, 1989) capture some of the periodicity properties, they do not show the partial reconnection currently observed in experiments. It would seem useful to construct the simplest possible nonlinear dynamical model to illustrate some of the temporal features of sawteeth. To this end, we introduce the variables $y(t)$ and $x(t)$, which represent the internal energy and the magnetic turbulence amplitude respectively. These are assumed to be governed by the pair of nonlinear differential equations

$$\tau_s \frac{dy}{dt} = (1 - \lambda x^2) + f_y(t) \quad (1)$$

$$\tau_s \frac{dx}{dt} = \lambda x(y-1)\phi(x,\lambda) + f_x(t) \quad (2)$$

where τ_s is a typical "ramp" time scale and λ is a large parameter. $f_y(t)$ and $f_x(t)$ are Langevin-type "noise" functions. Two simple heuristic choices have been tried for the function ϕ, namely $\phi = 1$ and $\phi = \frac{2\lambda x^2}{1+\lambda x^2}$. The Eq.(1) represents energy balance with confinement degradation in response to turbulence, while Eq.(2) represents the dynamic relationship between the plasma internal energy and magnetic turbulence. Both analytic and numerical solutions show $y(t)$ to have the characteristic sawtooth waveform for large λ with the sawtooth period $\tau_{period} = 2\tau_s(1 + \log\lambda/\lambda)$ and $\tau_{crash} = \tau_{period}\log\lambda/\lambda$. The variable $x(t)$ is small during the ramp but behaves in a δ-function-like manner during the crash. The effects of noise are investigated. The second model is found to be more robust to noise and has a physically more reasonable behaviour for $x(t)$ than the $\phi \equiv 1$ model. Both models suggest the possibility that the interplay of transport and dynamics is capable of yielding the gross temporal properties of sawteeth. Comparison with more elaborate numerical simulations suggests that the tentative interpretation of the dynamical variables may be a reasonable one.

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Two-Dimensional Gyrokinetic Simulation Studies*

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An efficient, 2D (sheared-slab), electrostatic, gyrokinetic code has been used to simulate η_i-mode instability, and a variety of features of the nonlinear solutions are studied:

Dimensional analysis applied to the gyrokinetic equations shows that in the limit of large density-scale-length L_n, all quantities can be written as constants times the *same* unknown function $F(\eta_i/s, T_e/T_i)$, where $s \equiv \frac{L_n}{L_{shear}}$. The performance of the code under numerical scaling tests will be presented; results indicate that the (time-dependent) non-linear solutions are robust and accurate enough to preserve this property, providing both a nice test for the code and a confidence-range over which larger (easier-to-simulate) gradient cases can be run and scaled to give results for the weaker gradients of experimental interest.

Fluid-code simulations of η_i instability have exhibited long-lived radially-extended structures[1] ("streamers"). These structures are generic in 2 and 3D without shear, and for a variety of models of FLR and parallel kinetic effects, but have never been observed in a gyrokinetic simulation. Progress in the attempt to identify the cause of the difference by comparing as-similar-as-possible fluid and gyrokinetic simulations in a 2D shear-free multiscale setting will be reported.

A set of moments of gyrokinetic-code data has been derived, enabling direct measurement of fluid-fluctuation correlations; inital results exploring the variance and cross-correlations of ϕ, $p_{\parallel}$, and $v_{\parallel}$ will be presented. Finally, a suite of particle diagnostics has been developed, with which we begin to identify and assess the relative statistical importance of diffusive, resonant and other (?) classes of particles.

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

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LINEAR STABILITY STUDY OF HIGH-n TRAPPED ELECTRON MODES FOR THE ATF TORSATRON*

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We are analyzing the linear stability of trapped electron modes [1] for the ATF torsatron [2]. We have found that the effects of the dissipative trapped electron modes can be changed by using the flexibility of the ATF torsatron. We found that shearless configurations are linearly unstable while those with strong shear are stable. The strongly unstable configurations have narrow eigenfunctions in ballooning space (localized in a field period) and therefore could be easily identified in the experiment; the largest growth rates are obtained for flux surfaces located half out in the minor radius. These results have been obtained considering peaked density profiles; for very flat density profiles a coupling to the sound wave is being considered.

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

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Steady-state dynamo and current drive in a nonuniform bounded plasma

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Current drive due to helicity injection and the dynamo effect are examined in an inhomogeneous, bounded, visco-resistive plasma. Averaged over a magnetic surface, there is in general no dynamo effect independent of resistivity - contrary to the results found previously for an unbounded plasma. The dynamo field is calculated explicitly for an incompressible fluid in the plane-slab model. In accord with our general conclusion, outside the Alfvén resonant layer it is proportional to the resistivity. Within the resonant layer there is a contribution which is enhanced, relative to its value outside the layer, by a factor $(\omega a^2/(\eta + \nu))$, where ω is the wave frequency, a the plasma radius, η the magnetic diffusivity, and ν the kinematic viscosity. However, this contribution vanishes when integrated across the layer. The remaining averaged field in the layer is enhanced by a factor $(\omega a^2/(\eta + \nu))^{+2/3}$ and is proportional to the shear in the magnetic field and the cube root of the gradient of the Alfvén speed. Although the current drive is enhanced in the layer, its efficiency is diminished, relative to outside, where it can be comparable to Ohmic. These results are interpreted in terms of helicity balance, and reconciled with the infinite medium calculations, by noting that the transverse flux of helicity is always proportional to η in the simple fluid model.

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TOKAMAK TRANSPORT DRIVEN BY QUASINEUTRALITY AND HELICAL ASYMMETRY

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Although the coefficient of the highest derivatives $\Delta\Phi$ in Poisson's equation goes to zero, rules of singular perturbation show that this quasineutrality condition remains the right equation to determine the electric potential Φ. It comes before the derivation of Ohm's law, whose conventional use to obtain Φ has been the source of anomalies in electron transport. Bifurcated three-dimensional equilibria should be employed to calculate the magnetic field in tokamaks because helical asymmetry models turbulence associated with net current and electrostatic microinstabilities. The level of asymmetry may be fixed by the requirement of quasi-neutrality. A Monte Carlo computer code has served to validate this theory, which raises a number of controversial issues, such as omitting conservation of momentum in the collision operator of the drift kinetic equation. The code runs so fast that the electric field can be found systematically from truncated quasineutrality conditions.

2D33

Relativistic relationship between toroidal rotation and charge density in tokamaks.

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Relativity connects measured charge densities in tokamaks with toroidal rotation. Relativistic changes on charge density are of the order of the charge density itself, at least in the case of neutral beam injection. This needs to be taken into account when trying to understand the differences in electron and ion radial transport rates, reflected by the plasma charge. For instance, enhanced confinement in ISX-B associated with counter neutral beam injection happens to correspond to a locally less charged plasma, when compared to the corresponding co-injection case.

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Destabilization of the Toroidicity-Induced Shear Alfven Eigenmode by Alpha Populations Using Fluid Moment Descriptions*

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Energetic plasma components, such as 3.5 Mev alphas, can couple to and destabilize discrete shear Alfvén gap (TAE) modes. This can result in new instabilities which are unique to ignited tokamaks and would not readily be observed in present experiments. Closed sets of fluid moment equations have been developed which include the necessary kinetic coupling and Landau damping physics to excite such instabilities. These have been solved using the 3-D initial value code FAR in toroidal geometry. Both beamlike and Maxwellian models have been considered for the hot species. The results show similar parameter scalings as analytic estimates and indicate the effects of continuum damping as multiple poloidal modes are included and profiles are varied. Linear growth rates and mode structure will be discussed as a function of variations in profiles, hot species parameters, resistivity, and toroidal mode number. A nonlinear model and code have also been developed, allowing studies of turbulent magnetic field saturation levels caused by the TAE mode.

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PLASMA EQUILIBRIA AS EXTREMAL STATES

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Fusion plasmas can "relax" to states that may be characterized as extremal. The process of relaxation may be complicated and turbulent, but it need not be. "Minimum energy," "maximum entropy," "minimum dissipation rate," and "minimum rate of entropy production" have stood as four distinct candidates for a governing principle that might regulate relaxation processes in guiding-center plasmas, Navier-Stokes fluids, and MHD fluids. Their predictive power depends upon constraints, which may appear as boundary conditions and/or approximate conservation laws. The resulting extremal states are few in number, compared to the number of states that appear for consideration before the variational principles are invoked. Nothing other than some kind of variational formulation has been suggested as a way of organizing our understanding as to *why* the profiles in confinement devices arrange themselves as they do. Ideal equilibria and linear instabilities have demonstrated only a *post facto* capability at this task.

Here, the relative capabilities and likely validity of the four principles are assessed, largely from the point of view of numerical evidence. Among other things, it is concluded that: (i) "minimum energy" is mainly relevant to the isolated initial-value ("decay") situation; (ii) "maximum entropy" and "minimum rate of energy dissipation" are the same[1] for continuous systems if entropy is properly defined, and related but distinct for discrete systems (such as discrete vortex models); (iii) for uniform temperature, and invoking the classic definition of entropy ($dS = \delta Q/T$), "minimum energy dissipation rate" and "minimum rate of entropy production" are the same; (iv) for non-uniform temperatures, "minimum rate of entropy production" has not yet been given an unambiguous formulation; and (v) no one of the four principles has yet been shown to have quantitative predictive power for steady-state turbulence, though the recent results of Chorin[2] are suggestive.

A recent MHD application[3] of some interest is the prediction of driven, dissipative equilibria with helically deformed current channels and the crucial, paired, vortical "convection cells," which have begun to appear in a variety of tokamak confinement experiments, first derived as a consequence of minimum-dissipation-rate calculations.

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1991 SHERWOOD INTERNATIONAL FUSION THEORY CONFERENCE
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A Simplified Approach to Pinch Equilibrium. N. A. SALINGAROS, University of Texas. --- The fundamental quantity in the usual MHD model is the magnetic field. We propose a formulation of pinch equilibrium in terms of the currents instead. An integral formulation of pinch equilibrium gives new kinetic pressure profiles for plasma configurations in a cylinder. This simplified method of computing magnetostatic equilibrium offers an alternative to solving the Grad-Shafranov equation. Its distinct logic leads to closed-form expressions obtained analytically. Results include the explicit dependence of equilibrium on the externally-generated field B_o , and field-reversal appears as an intrinsic feature of Screw-pinches. Basic insight into Z-pinches, Screw-pinches, and F-Θ relations comes from the same formalism.

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1991 Sherwood Theory Conference

ALPHA PARTICLE DESTABILIZATION OF THE TAE MODES*

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The high frequency, low mode number toroidicity-induced Alfven eigenmodes (TAE) are shown to be driven unstable by the circulating and/or trapped α-particles through the wave-particle resonances. For a poloidal harmonic to satisfy the resonance condition it requires that the α-particle birth speed $v_\alpha \geq v_A/2|m-nq|$, where v_A is the Alfven speed, m is the poloidal mode number, and n is the toroidal mode number. To destabilize the TAE modes, the inverse Landau damping associated with the α-particle pressure gradient free energy must overcome the velocity space Landau damping due to both the slowing-down α-particle and the core Maxwellian electron and ion distributions. The growth rate was studied analytically with a perturbative formula derived from the quadratic dispersion relation, and numerically with the aid of the NOVA-K code. Stability criteria in terms of the 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) parameters will be presented for TFTR, CIT, and ITER tokamaks. The volume averaged α-particle beta threshold for TAE instability also depends sensitively on the core electron and ion temperature. Typically the volume averaged α-particle beta threshold is in the order of 10^{-4} if the continuum damping effect is absent. Typical growth rates of the n=1 TAE mode can be in the order of $10^{-2}\omega_A$, where $\omega_A = v_A/qR$. Stability of higher n TAE modes will also be studied. Other types of global Alfven waves are stable due to sideband mode continuum damping resulting from toroidal coupling effects.

If the Alfven continuum gap does not exist across the whole minor radius, continuum damping exists for some poloidal harmonics. The continuum damping effect will be studied by employing both a resistive MHD stability code (NOVA-R)[1] and an analytical matching method, and the results will be presented.

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Theoretical Structure of Toroidal Alfvén Eigenmodes*

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The toroidal Alfvén eigenmode (TAE) is now of considerable interest for ignition experiments because of the possibility by that the universal diamagnetic drift microinstability drive of alpha particles can excite these waves, and in turn these waves can cause anomalous radial loss of alpha particles. We have formulated a theory that is applicable for arbitrary poloidal mode number m. The formalism resembles theories used to describe low frequency toroidal modes with singular structure at the rational surface, where an inner solution is matched to the outer solution using the global Δ' property. For the TAE mode, the outer solution is the continuum mode of the cylinder, which is characterized by a discontinuity in the perturbed displacement at the surface where $k_{\parallel}^2 V_A^2 = \omega^2$ ($\omega \equiv$ mode frequency, $k_{\parallel}$ parallel wave number, $V_A \equiv$ local Alfvén speed). With toroidal effects, the degeneracy of $k_{\parallel}(m) = -k_{\parallel}(m+1)$ allows two continuum modes that exist at one point to couple, and produce a continuous bounded perturbation in the inner region of the mode that matches in the outer region unto the continuum mode of the cylindrical theory. Using a generalization of degenerate quantum mechanical perturbation theory, a global dispersion is obtained for arbitrary m. The predicted eigenfrequency agrees with the results of a numerical shooting code and shows that $(\omega - \omega_G)/\varepsilon$ is a constant ($\omega_G \equiv$ gap frequency, $\omega \equiv$ eigen frequency, $\varepsilon \equiv$ inverse aspect ratio). For low m modes the MHD theory predicts damping of a TAE mode when the frequency resonates with the Alfvén continuum outside the inner-gap structure. With Landau's causality prescription, the damping rate can be calculated perturbatively. For low m-numbers this damping competes with the alpha particle instability drive, leading to criteria for instability. For intermediate m-numbers, the resonance damping mechanism disappears when $m \approx 1/\varepsilon$ since relatively close successive gaps arise that prevent local Alfvén resonance from occurring. The stability criteria now relies on the competition between the kinetic alpha particle response and global Landau damping due to the background plasma. The relatively narrow structure of the intermediate m-gap modes reduces the alpha particle drive due to orbit effects and enhances the background Landau damping, which was insignificant for low m. For high $m >> 1/\varepsilon$ it is found that the usual ballooning mode theory is inapplicable since the mode width $\Delta_m \approx \varepsilon r/m$ is narrower than the spacing between resonances, $\Delta_s \approx r/m$. For this case a large order determinant is obtained, which can be exactly diagonalized as $m \to \infty$. The eigen-frequency is found to exist just at the boundary between the gap and continuum. This structure implies an extremely localized mode for high m, which implies strong bulk Landau damping.

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A Tearing Mode Energy Principle for an Axisymmetric, Finite Beta Configuration

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An energy principle for finite beta tearing modes has been developed for the cylindrical pinch and is being extended to axisymmetric systems. It is similar to the standard energy principle for ideal stability. Recall that slow-growth-rate modes, both resistive and ideal, have all their inertia concentrated in thin layers localized on resonant surfaces. Growth rates are obtained by matching between outer solutions and inner solutions. The conditions for the second order equation are that a large solution match and a small solution match. When ideal MHD theory is used for the inner layer, the coefficient matching to the outer large solution nearly vanishes. Thus, in ideal theory only the small outer solution need be considered. It is straightforward to construct a convergent bilinear energy that contains the essence of the ideal stability problem.

The solutions of the resistive inner layer equations can be matched to large outer solutions. Thus, it is necessary to consider large solutions in the outer region. A naive attempt to incorporate the large solutions in the ideal energy leads to divergences. However, Pletzer and Dewar [1] have shown how to treat the large solution in a convergent way that is consistent with the ideal energy. Large solution elements are added to the set of functions, and carefully crafted, convergent matrix elements are formed.

Simple approximations to the behavior of the inner solutions lead to an energy type of stability criterion. These approximations are not verified in Ref. 2. The difference is that between a marginal stability criterion of $\Delta' = 0$, and one with a finite value. As is generally true when an energy principle and an eigenvalue principle disagree, there are arguments on both sides.

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Collisionless Magnetic Reconnection*

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Although the first theory [1] of collective modes producing magnetic reconnection in collisionless plasmas was reported more than 25 years ago, laboratory experiments attaining the very high temperature regimes where these modes can be excited have come into reality only recently [2]. These experiments involve electron temperatures in the 5 to 10 keV range obtained by suppressing, by the injection of a significant population of "high energy" nuclei, the onset of macroscopic modes producing magnetic reconnection due to the effects of finite electrical resistivity [3]. The latter type of mode is in fact considered to be responsible for the crash phase of the so-called "sawtooth oscillations" of the central part of the plasma column.

The high temperature regimes thus obtained are subject to sudden collapses (so-called "monster sawteeth") that we attribute to collisionless modes producing magnetic reconnection [4] and having a prevalent poloidal number $m^o = 1$. The early analyses that were applied to space physics [5] had shown that collisionless reconnection tends to develop only weakly in plasma configurations that have a relatively large stability margin against the onset of ideal MHD mode. On the other hand, a magnetically confined axisymmetric plasma can have relatively low stability margin against ideal MHD ($m^o = 1$) modes and consequently is susceptible to strong collisionless reconnecting modes. We find that the relevant growth rates have numerical values consistent with the characteristic times of the observed collapses. The smallest characteristic distance involved is $d_e = c/\omega_{pe}$ and therefore these modes can be classified as of the "inertial" type [1], even though, unlike the modes treated in Ref. [1], they cannot be described by fluid equations. The second characteristic distance is the ion gyroradius ρ_i, and the third is the radius r_1 where $q(r_1) = B_\phi r_1/(B_\theta R) = 1$. We refer, for simplicity to a configuration where the magnetic field is represented by $\underline{B} \simeq B_\phi(r)\underline{e}_\phi + B_\theta(r)\underline{e}_\theta$. The mode growth rate [4] is about $\gamma \simeq [V_A d_e + 0.3c\lambda_{De}(1+T_i/T_e)^{1/2}]/(r_1 L_s)$ where $1/L_s = (r_1/R)dq/dr$.

The linearized theory breaks down for very small values of the perturbed magnetic field $\tilde{B}_r$, when the size of the magnetic island $\delta_I \sim d_e$. We note that $\delta_I \propto \tilde{B}_r^{1/2}$. A theoretical model to extend the analysis beyond the point where $\delta_I \sim d_e$ is proposed assuming that the electrons are scattered over the region δ_I and lose momentum at a rate corresponding to a magnetic diffusion coefficient $D_m \sim \gamma\delta_I^2$. This leads to δ_I replacing d_e as the smallest scale distance of the problem and to preserve γ of the order of $c\lambda_{De}/(r_1 L_s)$ while a new form of the relevant dispersion equation, that is similar to that of the linearized theory, is solved. The latter feature is consistent with the experimentally observed fact that the growth rate of the instability remains about constant, well beyond the limits of the linearized theory. *Sponsored in part by the U.S. Department of Energy.

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DERIVATION OF A REDUCED KINETIC EQUATION USING LIE-TRANSFORM TECHNIQUES*

LBL-30399

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The asymptotic elimination of fast time scales from a general kinetic equation, of the form: $\partial_t f + \dot{\mathbf{z}}\cdot\partial_{\mathbf{z}} f = \mathcal{C}[f]$, facilitates the study of the long time behavior of its solution $f(\mathbf{z},t)$. Here $\dot{\mathbf{z}}$ describe the single-particle Hamiltonian dynamics and the operator $\mathcal{C}$, which may possess nonlinear functional dependence on f, describes processes (such as discrete-particle effects, resonant wave-particle effects, or effects due to external sources) which cause changes in f as it is convectively transported along a Hamiltonian phase-space trajectory. When a fast time scale is associated with $\dot{\mathbf{z}}$ through the dependence on a fast angle θ (whose frequency $\dot{\theta} = \Omega$ satisfies $\epsilon \equiv 1/\Omega\tau \ll 1$, where τ is a slow time scale of interest), a near-identity phase-space transformation $T_\epsilon : \mathbf{z} \rightarrow \mathbf{Z}$ (carried out with Lie-transform techniques) yields reduced Hamiltonian dynamical equations $\dot{\mathbf{Z}}_\epsilon$ which are θ-independent. The corresponding transformed kinetic equation is

$$\frac{\partial F(\mathbf{Z},t)}{\partial t} + \dot{\mathbf{Z}}_\epsilon \cdot \frac{\partial F(\mathbf{Z},t)}{\partial \mathbf{Z}} = \mathcal{C}_\epsilon[F](\mathbf{Z},t), \tag{1}$$

where the transformed distribution function F and operator $\mathcal{C}_\epsilon$ still exhibit θ-dependence.

Averaging Eq. (1) over the fast angle θ yields a kinetic equation for $\langle F\rangle$, the θ-averaged part of F: $d_{\mathrm{R}}\langle F\rangle(\mathbf{Z}_{\mathrm{R}},t)/dt = \langle \mathcal{C}_\epsilon[F]\rangle(\mathbf{Z}_{\mathrm{R}},t)$, where $\mathbf{Z}_{\mathrm{R}}$ describe the reduced Hamiltonian dynamics $\dot{\mathbf{Z}}_\epsilon$, and the reduced operator $d_{\mathrm{R}}/dt = \partial_t + \dot{\mathbf{Z}}_{\mathrm{R}}\cdot\partial_{\mathbf{Z}_{\mathrm{R}}}$ is $\mathcal{O}(1/\tau)$. In general, the θ-dependence of $\mathcal{C}_\epsilon$ couples the kinetic equations for $\langle F\rangle$ and $\widetilde{F}$, the θ-dependent part of F. One solves for the Fourier coefficient $\widetilde{F}_l$ (associated with $e^{il\theta}$) as a functional of $\langle F\rangle$: $\widetilde{F}_l = -i\ \widetilde{\mathcal{C}}_l[\langle F\rangle]/l\Omega + \mathcal{O}(1/\Omega^2)$, where $\widetilde{\mathcal{C}}_l$ is the Fourier coefficient of $\mathcal{C}_\epsilon$. One obtains a reduced kinetic equation for $\langle F\rangle$: $d_{\mathrm{R}}\langle F\rangle/dt = \mathcal{C}_{\mathrm{R}}[\langle F\rangle]$, where the reduced operator $\mathcal{C}_{\mathrm{R}}$ is

$$\mathcal{C}_{\mathrm{R}}[\langle F\rangle] = \langle \mathcal{C}_\epsilon\rangle[\langle F\rangle] - \sum_{l\neq 0} Im\left\langle \widetilde{\mathcal{C}}_l\left[\frac{e^{-il\theta}}{l\Omega}\,\widetilde{\mathcal{C}}_l^*[\langle F\rangle]\right] e^{il\theta}\right\rangle + \mathcal{O}(1/\Omega^2). \tag{2}$$

General expressions for $\mathcal{C}_{\mathrm{R}}$ are given, as well as expressions for the guiding-center and oscillation-center phase-space transformations of a linear Fokker–Planck operator. A discussion of the relationship with Mynick's work [H.E. Mynick, J. Plasma Phys. **39**, 303 (1988)] will be presented.

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SHERWOOD THEORY MEETING 1991

The LOCUS Interface to the MFE Database*

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The MFE database now consists of over 900 shots from TFTR, PDX, PLT, T-10, JT-60, TEXT, JET and ASDEX. A variety of discharge conditions is represented, ranging from single time slice Ohmic discharges to multiple time-slice auxiliary heated discharges. Included with most datasets is a reference that describes the experiment being performed when the data was taken.

The MFE database is currently implemented under INGRES† on a VAX that is on Internet. LOCUS§, a database utility, developed at the Princeton Plasma Physics Laboratory is now available as an interface to the database. The LOCUS front end provides a graphic interface to the database from any generic graphics terminal that supports Tektronix 4010 emulation. It provides a variety of procedures for extracting, manipulating and graphing data from the MFE database.

In order to demonstrate the capabilities of the LOCUS interface, we will examine, in detail, one of the recently added JET, H-mode discharges. In this example, we will address some new concepts such as *monitor functions,* which have been introduced in order to help users more fully understand the multiple time-slice datasets. We will also describe some of the more advanced techniques available in LOCUS for data access and manipulation. Specific areas of interest that will be discussed are searching for and retrieving datasets, graphics, data fitting, and linear regression analysis.

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* Supported by USDOE Grant DE-FG05-88ER53266

† INGRES is a trademark of Relational Technology Inc.

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Stabilization of resistive internal kinks by energetic particles *

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In order to properly explain experiments, such as (for instance) those carried out in JET [1] and TFTR [2], where sawtooth-free operation was achieved despite the fact that the magnetic winding index $q(r=0)$ was smaller than unity, a model should show that resistive as well as ideal internal kink modes $(m^0 = 1)$ are stable [3]. In this work, we analyze the role played by (i) finite ion diamagnetic, $\omega_{di} = (c/enB_\theta R)(dp_i/dr)$ and (ii) electron drift wave, $\hat{\omega}_{*e} = -(c/enB_\theta R)[T_e dn/dr + n(1.71)dT_e/dr]$, frequencies at the $q(r) = 1$ surface, and (iii) finite $1 - q(0)$ in the stabilization of these modes by energetic particles. The first (i) and third (iii) factors play an important role at the "point" $\lambda_H + Re(\lambda_k) = 0$ where a purely growing mode, destabilized by resistivity is found [4]. Here λ_H and $\lambda_k(\omega)$ are proportional to the potential energy functionals of the core plasma and energetic species, respectively, in response to the perturbation. The second factor, (ii), is necessary to make complete stabilization possible [5] at $\lambda_H + Re(\lambda_k) \leq \lambda_C < 0$ where the critical value is a function of $\hat{\omega}_{*e}$ and $Im(\lambda_k)$. Numerical solutions of the relevant dispersion relation are presented, incorportating (among other) varying levels of velocity space anisotropy in the equilibrium distribution function of energetic particles, as well as of peakedness in their pressure profile.

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

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Cyclotron Harmonic Emission from the Generalized Kirchhoff's Law

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It was shown recently[1-4] that mode conversion phenomena has a profound influence on the emission of radiation from a nonuniformly magnetized plasma. Whenever the emitting layer is localized due to gradients of the external magnetic field, mode conversion leads to the Generalized Kirchhoff's Law (GKL) $A_1/E_1= A_2/E_2= A_3/E_3=I$, where A_j represents the absorbed fraction on the j-th wave branch, E_j is the corresponding emitted energy along j-th branch and I is some fundamental constant depending upon basic plasma parameters. As the relations between emission and absorption were deduced from qualitative thermodynamic arguments using only the law of equipartition of energy and the reciprocity relations[1], they do not depend on details of the source or sink if their distributions fall off quickly enough as $|z|\to\infty$[3]. It follows from the GKL[1,2,4] that cyclotron radiation from a mode conversion layer is asymmetric for harmonics of both the ion and electron cyclotron frequencies. This asymmetry should be taken into account in plasma diagnostics and other applications to avoid errors in the interpretation of experimental results.

In order to understand the main physical processes underlying the GKL it is important to obtain the explicit expressions for A_j and E_j from the governing mathematical model. In this paper we have considered a model based on the fourth-order mode-conversion-tunneling equation[1,3], and have discovered new important properties of linearly independent solutions of the adjoint problem. Using the properties obtained and the results of [3] we have found the general but simple expressions for absorbed and emitted wave power:

$$A_j=a_j\int w(z)|\Psi_j(z)|^2dz\,, \quad E_j=a_j|\int s(z)\Psi_j(z)dz|^2\,, \quad j=1,2,3. \qquad (*)$$

Here each Ψ_j is a wave solution of the adjoint of the mode-conversion-tunneling equation with absorption, w(z) and s(z) are sink and source functions respectively and all a_j are known constants. Usually the sink distribution is associated with the plasma dispersion function (nonrelativistic or relativistic) but the formulas obtained are valid with any w(z) which falls faster than $|z|^{-1/2}$.

The formulas (*) permit us to analyze any questions related to the GKL. We considered the N-point approximation for relating sink and source, since due to the fluctuation-dissipation theorem any absorber is also an emitter and vice versa. For a one-point delta function source and sink approximation (the case of very small parallel wave number), the GKL has been shown to be satisfied for an arbitrary source strength[1,2], which now follows immediately from (*). The cases of N>1 are more complicated since the solution of the integral equation for Ψ involves inverting a complex NxN matrix. For a two-point model, which we have developed both with and without self-absorption, the second source point is a function of the first source and the two sinks. In the general case of arbitrary N, any of N-1 source points may be chosen arbitrary, since the GKL only imposes two conditions. Thus the GKL is consistent with nearly any N-point model. This actually represents a direct proof of the GKL from the governing equation in the discrete case. On the other hand, we believe that the GKL can give the information about the distributed source when additional physical considerations are involved.

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Effect of drift-Alfvén wave fluctuations on internal resistive kink

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In several tokamak experiments it has been observed that sawtooth oscillations deviated substantially from pure MHD predictions. These experiments, notably Tokapole II [1], Textor [2] and others since then, have reported an absence of total reconnection after the sawtooth crash. The safety factor on the axis is seen to be frozen below unity throughout the sawtooth period in contradiction with the Kadomtsev theory. Simultaneously with the breakdown of this theory a large magnetic turbulence has been measured at Tokapole II [3] in the vicinity of the inversion radius. In this paper we investigate a possible mechanism through which the magnetic turbulence can inhibit the reconnection. The fluctuations can affect the stability of the m=1 tearing mode, the presumable cause of the sawtooth crash, through a dynamo-like mechanism in which they induce an effective electric field which modifies the resistive layer equations. As an example, we consider fluctuations due the drift-Alfvén waves which are consistent with the observed turbulence. Following the treatment of Coppi et al. [4] we derive the dispersion relation which shows that the tearing mode growth rate can be reduced by fluctuations. We discuss its consequences for sawtooth oscillations.

This research has been supported by the Israeli Academy of Science and the U.S. Department of Energy.

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ELIMINATING VACUUM MAGNETIC FIELD ASYMMETRIES IN TOKAMAKS*

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Disruptions in tokamaks are often preceded by m=2, n=1 magnetic oscillations. These oscillations, generally considered to be resistive tearing modes, often rotate, slow down, and lock on to a particular toroidal phase. When the modes lock, they can increase in amplitude. The toroidal phase at which they lock has been observed to correlate well with known vacuum magnetic field asymmetries.

An obvious strategy is to minimize the sources of toroidal asymmetries. Since coils cannot be placed with infinite accuracy in real machines, there will be remnant asymmetries which cannot be eliminated.

One way to minimize the effects of the remnant vacuum magnetic field asymmetries is to introduce known, controllable compensating asymmetries. This strategy has been successfully carried out on the Auburn Torsatron[1].

For a given remnant asymmetry, the amplitude of compensating asymmetric **B** fields is determined by minimizing the appropriate vacuum **B** island sizes, using the IFT (Integrable Field Torsatron) code[2]. The vacuum magnetic field is given a rotational transform by adding a circular coil located at the magnetic axis. Results of compensating a toroidal field coil shift with a slight displacement of a poloidal field coil will be presented.

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General Analysis of Magnetic Loop Positioning for Plasma Control in Ignition Tokamaks*

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The control of the plasma vertical position in tokamak configurations and the positioning of magnetic, pick-up loops are considered. A 1 $\frac{1}{2}$ D transport and free-boundary equilibrium code^{+} (DINA) is utilized. The equilibrium problem for a plasma with free-boundary is solved using the inverse-variable technique. Circuit equations for eddy currents in the vacuum vessel, eddy currents in structures, and currents in active coils coupled with the plasma equilibrium and transport equations are solved. The numerical algorithms employed in the solution permit a reduction in computer time of about two orders of magnitude over conventional calculations of coupled equilibrium and transport.

The influence of the location of pick-up coils on control of the plasma vertical position is examined. It is shown that there are geometrical arrangements of the magnetic loops such that the plasma vertical position can not be controlled using a conventional control law (this is regardless of the resistivity of the passive conductors and the gain value in the control system). An explanation of this phenomenon is given. A new and simple control law is proposed such that plasma control is possible with general positioning of the magnetic loops. Our conclusions should be important for the operation of ignition tokamaks, where elongated, high-current plasmas have to be stabilized with magnetic loop positioning subject to severe constraints.

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An Unstructured Second-Order Godunov Method for Transverse MHD

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The Godunov method[1] and its higher-order extensions[2,3,4] have been very successful in treating flows with shock waves in gas dynamics. These algorithms for the inviscid Euler equations are based on exact local solutions to the Riemann problem. They have the desirable properties of being able to describe shock waves and contact discontinuities with a width of only a few mesh points, while preserving monotonicity in the physical variables (i.e., they are non-oscillatory). We have extended the Godunov method to the MHD equations, in order to simulate plasmas with small viscosity and resistivity. In the case of the transverse MHD model (a 2D system in which all quantities vary in the $x-y$ plane, with a magnetic field transverse to the flow, i.e., $\mathbf{B} = B_z(x,y)\hat{\mathbf{z}}$, with flow velocity $\mathbf{v} = v_x(x,y)\hat{\mathbf{x}} + v_y(x,y)\hat{\mathbf{y}}$), the Riemann problem can be solved exactly. We have developed a 2D code which uses unstructured adaptive triangular meshes,[4] and which is based on a magnetic Riemann solver. This code is particularly suited to modeling realistic geometries. We will describe applications of this code to implosive plasma phenomena, including plasma pinches.

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Theory and Simulation Study of Surface Waves in Bounded Plasma

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Surface waves have been investigated analytically and with particle simulation for an unmagnetized 2d plasma slab with periodic boundary conditions in y and bounded in x with either vacuums (isolated plasma) or conducting walls. In the vacuum boundary case, the particle simulation results are found to agree reasonably with theory for high frequency surface waves.[1] For a plasma inside two absorted conducting walls, simulation indicate that surface waves propagate along the static sheath-plasma boundary. Analytically treating the sheath as a vacuum layer, the surface waves bear a resemblance to plasma-vacuum surface waves with the vacuum dielectric constant ϵ_0 replaced by $\epsilon_0 \arctan(k_y \Delta)$, where Δ is width of the static sheath. Nonlinear interaction of bulk and surface waves in the system will be discussed.

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Presheath and Current-Free Double Layer in a Two-Electron-Population Plasma or a Plasma with Negative Ions*

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An edge plasma close to the RF antenna, which has a nonthermal energetic electron population, and a plasma for the negative ion source have two populations of negative charged species. The development of the potential near the wall is treated for such a plasma with two populations. The plasma equation is analytically solved to show the possibility of steady-state potential formation in the plasma and to obtain the potential drop in the presheath.

The potential drop in the presheath considerably depends on the relative densities of the two populations. It discontinuously changes from the value of the order of kTc/e to one of the order of kTh/e where Tc is the effective temperature of the cold population and Th is one of the hot population. This happens when the ratio of the particle density of the energetic population to one of the cold population nh/nc becomes greater than a certain value of the order of 0.1. It is also shown that a current-free double layer[1] can be steadily formed in the plasma when the ratio nh/nc is of the order of 0.1. The double layer is formed so as to connect two presheath potentials with different values. The position and amplitude of the double layer are controlled by changing the ratio nh/nc and a spatial distribution of the particle source.

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Drift Wave Vortices in Inhomogeneous Plasmas and Sheared Magnetic Fields*

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The effects of density and temperature gradients on drift wave dynamics are studied using a fully nonlinear model with the Boltzmann density distribution. The equation based on the Boltzmann relation, in the short wavelength ($\sim \rho_s$) region, possesses no localized monopole solution while in the longer wavelength $\sim(\rho_s\rho_n)^{1/2}$ region the density profile governs the existence of monopole-like solutions. In the longer wavelength regime, however, the results of analysis show that due to the inhomogeneity of the plasma the monopoles cannot be localized sufficiently to avoid coupling to propagating drift waves. Thus, the monopole drift wave vortex is a long-lived coherent structure, but it is not precisely a stationary structure since the coupling results in a flapping tail; the simulation supports the results.

The effect of magnetic shear on the vortex is also studied. A monopole-like vortex equation which includes the effects of density and temperature gradients and magnetic shear is derived. The presence of the magnetic shear makes localized, though not strictly localized, monopole-like solution possible in the short wavelength ($\sim \rho_s$) region in which such solutions do not exist when the magnetic shear does not exist as shown above. The monopole-like solution is found numerically in the one dimensional case.

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Implementing a Fully Implicit Numerical Scheme in a 2-D Fluid Code with the Krylov Method *

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In order to obtain a robust 2-D fluid code for modeling the edge-plasma region of a tokamak, we have implemented an implicit method-of-lines scheme utilizing the Krylov technique.[1] The motivation for this work comes from the success of a different implicit scheme reported recently,[2] and from the expectation that the electrostatic potential can be solve for unambiguously using a fully implicit algorithm. Here, we solve a coupled set of temporal ordinary differential equations for the variables (particle, parallel momentum, and electron and ion energy densities) at each spatial grid point. Portions of the existing B2 code[3] are used to evaluate the spatial derivatives for the right-hand sides of the ODE's. The Krylov method which solves the ODE's does not require formation or solution of the Jacobian matrix explicitly. However, in order to obtain efficient performance, one needs to precondition the problem by obtaining an approximate solution. The potential payoff is that the required approximate solution may be cheaper to compute than the full Jacobian. We have used a variant of the original B2 solution[3] as a preconditioner and also a banded matrix approximation to the Jacobian which keeps many of the couplings in the poloidal direction. Both preconditioners show a similar substantial increase in speed compared to using no preconditioner. The overall performance is not yet optimal in comparison to other diffusion problems which have used this technique. We shall report on additional modifications to the preconditioner in order to realize better performance, and compare the method to the original B2 solution in terms of speed and robustness.

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MHD STABILITY THEORY FORMULATED IN TERMS OF A SCALAR REPRESENTATION

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A recently proposed representation of MHD in terms of stream functions and potentials is further developed in order to treat stability problems on various levels of complexity. In the first part of this work, nonlinear reduced MHD equations are derived, for which an energy principle for stability is established. For a toroidal plasma, this energy principle yields the same ideal MHD stability limits as the appropriate aspect ratio expansion of the full MHD equations.The nonlinear reduced equations allow us to formulate the problem of the bifurcation of a solution of the internal kink type. In the second part of this work, we generalize our representation of MHD to include kinetic effects. As in the pure MHD case, we introduce a stationary reference magnetic field B_0 (which need not be a static equilibrium field) to describe the particle motion and to express the distribution functions. The general features of this formulation, which allows to treat nonlinear problems including kinetic effects, are discussed.

Map Model for Alpha Particle Containment with Toroidal Alfvén Eigenmode*

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The Toroidal Alfvén Eigenmode (TAE) tends to highly localize in space centered about resonant surfaces where $k_{\|}(m) = -k_{\|}(m + 1)$, where $k_{\|}(m)$ is the parallel wave number of the mode that is dominated by the m^{th} poloidal harmonic. For many parameters the width of the mode is smaller than the orbit excursion of an alpha particle from a flux surface. This is certainly true for moderate and large m numbers, and is even marginally applicable for the lowest m modes. This situation suggests that a mapping technique will be relevant for describing the diffusion of an alpha particle in the presence of the TAE mode. When an alpha particle passes through a resonate surface it receives a kick that can be precisely calculated in the limit we have described. This kick primarily causes a change in the unperturbed canonical angular momentum of the particle. A map can readily be constructed that relates the phase and strength of kick for successive interactions. Various parameters will be chosen to display how global stochasticity develops as a function of the perturbed field strength as well as the perturbed spectrum.

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Effect of Nonstandard Trapped Particle Orbits on m = 1 Perturbations*

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Considerable evidence now exists that hot particles within the q = 1 surface of a tokamak improves the stability of the m = 1 mode. This is particularly evident for the monster sawtooth phenomena in JET, where high energy particles (~ 1 MeV) are created in the tokamak center by ICRF heating. Previous theories have generally assumed that the kinetic effects of the high energy particle response can be described using banana orbit theory, where the particle displacement from a flux surface is small compared to the flux surface radius. This assumption does not satisfy experimental conditions, and a more general orbit description is needed to describe the correct kinetic response to the perturbed MHD energy. The theory was reported previously[1] and the quantitative numerical results will be reported here for a class of equilibria of hot particles. The differences between the theories of using banana orbits and using the correct orbits will be emphasized.

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Gyrokinetic Numerical Simulation Studies of Unstable η_i Modes*

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In slab geometry, unstable η_i modes with the same "azimuthal" mode number localized at neighboring mode rational surfaces can superpose to form a coherent quasi-mode (by appropriately choosing the initial conditions) such that plasma heat flow over a large "radial" distance arises. We have numerically simulated such flows in a sheared magnetic field for realistic experimental parameters ($L_n/L_s \sim \cdot 1$, $\eta_i \sim 2 - 4$, $T_e/T_i \sim 1$). We find that these coherent quasi-modes are unstable to perturbations which result in the break-up of the quasi-modes into small vortices with length scales characteristic of the widths of the individual localized modes. The final stationary turbulent state is essentially the same as that reached when the instabilities grow from random noise.

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Alpha Particle Motion in Toroidal Alfvén Eigenmodes*

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The stochastic threshold of alpha particle motion in given toroidal Alfvén eigenmodes (TAE) is studied. In particular we consider alphas near the toroidal trap-pass boundary, where the bounce frequency is small. The resonance condition is

$$\omega = n\, \omega_d + p\, \omega_b$$

where n, p are integers. For small ω_b many resonance levels with different p's are close to each other. The closeness of these resonance levels indicates that the alpha particle motion is likely to be stochastic. We present a Hamiltonian formalism for the alpha particle motion which can be used, together with the resonance overlapping argument, to calculate the size of stochastic region for given TAE amplitudes.

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Computer Simulation of Transport Driven Current in Tokamaks

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Transport phenomena can significantly increase the toroidal current over that driven directly by the O.H. electric field. The bootstrap current theory accounts for the effect of banana diffusion on toroidal current in the large aspect ratio limit, but anomalous transport and toroidal geometrical effects cause significant modifications. 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, also without any O.H. electric field, show that an initial toroidal current decays slower than the magnetic diffusion resistive decay time would indicate. Since this occurs in the highly collisional regime, in which the standard bootstrap theory does not apply, it suggests the existence of a dynamo current drive mechanism which is not yet well understood. The simulations also show that electrostatic potential and pressure are not constant over a flux surface, possibly due to particle trapping. The self-consistent electrostatic potential has a significant effect on both transport and equilibrium, and is easier to study in simulations than in theory or experiments.

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TOKAMAK FORMATION AND SUSTAINMENT BY TOKAMAK INJECTION*

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We propose here a new helicity injection method for tokamak formation and sustainment that has high efficiency, conserves toroidal symmetry and is inductively driven. The basic idea is to inject a small tokamak (source tokamak) into a larger tokamak (steady tokamak). This current drive scheme eliminates the need for the ohmic heating transformer in the steady tokamak allowing the formation of very small aspect ratio tokamaks (Spherical Tori). Thus, steady state operation and high beta can be realized simultaneously. The method can also be applied to a larger aspect ratio tokamak and used in conjunction with the standard inductive formation technique.

In order to allow for translation the ohmic heating coil used to produce the source tokamaks must be fed from one end (as in the CSS device[1]) and the toroidal field coil must link both tokamaks. After formation the source tokamaks are accelerated towards the steady tokamak by a mirror field and the tension of the field lines that wrap around both tokamaks (producing a "doublet" type configuration).

In a tokamak the helicity is proportional to the current. This indicates that (assuming helicity is conserved during the merging process) a steady state situation will result if the helicity supplied by the source tokamaks is equal to the helicity dissipated by the steady tokamak. Assuming that source tokamaks of helicity K_s are injected with frequency f, the steady state condition can be written as:

$$f\, K_s = 2\, V_t\, \Psi_t = K_t \,/\, \tau_K$$

where V_t, Ψ_t, K_t and τ_K are the ohmic loop voltage, toroidal flux, helicity and helicity decay time of the steady tokamak. A simple calculation shows that the DIII-D tokamak could be sustained by injecting source tokamaks with R=1.20 m, a=0.23 m and I=151 kA at a frequency of 120 Hz.

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SHERWOOD THEORY 1991

Ideal Instability of Shear Flow with Magnetic Field*

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ABSTRACT

Magnetohydrodynamic shear flow instabilities are investigated. Of particular interest is the role of the magnetic field on the Kelvin-Helmholtz instability. A simple condition for instability is given for plane parallel equilibria with antisymmetric shear flow and either symmetric or antisymmetric magnetic field[1]. The condition is obtained by a novel method, of perhaps general utility, that uses the Nyquist method together with symmetry. Several applications will be given. For example, application of the condition to a plane parallel Couette type flow, which is stable in the absence of magnetic field, shows that the presence of magnetic field can render the system unstable. Also, although strong magnetic shear can stabilize shear flow with a hyperbolic tangent profile, there exists a range of magnetic shear that causes destabilization.

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Optimum Theory for the Energy Dissipation in a Pinch

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It was first suggested by Howard /1/ that rigorous bounds may be obtained for a physical quantity characterizing a turbulent state by extremizing the quantity subject to a set of integral constraints.This optimum theory of bounds has led to interesting results in fluid dynamics /2/, and has been applied recently to problems in plasma turbulence / 3,4/. In this paper, we obtain a lower bound for the total energy dissipated (or equivalently, a lower bound for the toroidal current) in a pinch. This lower bound is computed subject to the energy and helicity balance constraints, and the conservation of toroidal flux. In order to compare our results with those of Ref. 3, numerical solutions are computed for a single m=1, k=-2 mode with the energy constraint for a Hartmann number of 200. Our results are different from those of Ref. 3; we give reasons for the differences. The magnetic field-reversal occurs at $\theta \simeq 1.9$. The minimum current for the onset of field-reversal is 150 kA for the parameters of ZT-40M, not inconsistent with observations /5/. We then improve the lower bound by including the helicity constraint as well. A set of natural boundary conditions is derived from the variational principle, and the singularities of the Euler equations near the magnetic axis are cured by imposing regularity requirements on the solutions for the magnetic, velocity and vorticity fields and the current density. Numerical results will be presented.

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Studies of the Deformable Effects on the Feedback Stabilization of Axisymmetric Modes in Tokamak Plasmas*

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A new linear MHD stability code, NOVA-W, is described and applied to the study of the feedback stabilization of the axisymmetric mode in deformable tokamak plasmas. The NOVA-W code is a modification of the non-variational MHD stability code NOVA [C. Z. Cheng and M. S. Chance, J. Comp. Phys. **71** (1987) 124] that includes the effects of resistive passive conductors and active feedback circuits. The vacuum calculation has been reformulated in terms of the perturbed poloidal flux to allow the inclusion of perturbed toroidal currents in the region surrounding the plasma. The boundary condition at the plasma-vacuum interface relates the instability displacement to the perturbed poloidal flux.

The NOVA-W code is used to examine the effects of plasma deformability on feedback stabilization. It is seen that plasmas with strongly shaped cross sections have unstable motion different from a rigid shift. Furthermore, the placement of passive conductors is shown to modify the non-rigid components of the motion in a way that reduces the stabilizing effects of these conductors. Passive feedback results using several equilibria, including the CIT design equilibrium, will be presented.

The eigenfunction is also modified under the effects of active feedback. This deformation is seen to depend strongly on the position of the flux loops which are used to determine plasma vertical position for the active feedback system. The variations of these non-rigid components of the eigenfunction always serve to reduce the stabilizing effect of the active feedback system by reducing the measurable poloidal flux at the flux-loop locations. Active feedback results will be presented for the PBX-M tokamak configuration.

The NOVA-W code is presently being adapted for the highly shaped TCV design equilibrium. Initial results for the TCV configuration will also be presented.

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TOKAMAK ROTATION AND CHARGE EXCHANGE*

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In the absence of momentum input, tokamak toroidal rotation rates are typically small -- no larger in particular than poloidal rotation -- even when the radial electric field is strong, as near the plasma edge. This circumstance, contradicting conventional neoclassical theory, is commonly attributed to the rotation damping effect of charge exchange, although a detailed comparison between charge-exchange damping theory and experiment is apparently unavailable. Such a comparison is attempted here in the context of recent TEXT experiments[1], which compare rotation rates, both poloidal and toroidal, in helium and hydrogen discharges. The helium discharges provide useful data because they are nearly free of ion-neutral charge exchange; they have been found to rotate toroidally in reasonable agreement with neoclassical predictions. The hydrogen experiments show much smaller toroidal motion as usual. The theoretical calculation uses the full charge-exchange operator and assumes plateau collisionality, roughly consistent with the experimental conditions. We calculate the ion flow as a function of ν_{cx}/ν_c, where ν_{cx} is the charge exchange rate and ν_c the Coulomb collision frequency. The results are in reasonable accord with the observations.

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Neoclassical Transport Coefficients for Tokamaks with Bean-Shaped Flux Surfaces[1]

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Abstract

Simple analytic representations of the neoclassical transport coefficients for indented flux surfaces are presented. It is shown that a transport coefficient for an indented flux surface can be expressed in terms of a linear combination of the previously known transport coefficients for two nonindented flux surfaces. Numerical calculations based upon actual equilibria from the PBX-M tokamak indicate that, even for modestly indented flux surfaces, the ion neoclassical thermal transport can be over a factor of two smaller than in a circular plasma with the same midplane radius or with the equivalent area.

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3C25

A Numerical Method for Solving Reaction Rate Equations*

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The numerical solution of differential equations for reacting species on a spatial grid is generally a difficult problem. The stiffness of the system of equations requires an implicit solver. Nonlinearities require that a quadratically convergent iterative method such as Newton-Raphson be used at each time step. This requires finding the Jacobian of the finite difference form of the differential equation, solving this matrix equation for each iteration, and storing this Jacobian in memory to allow vectorization of the problem. A method is described that eliminates these difficulties for such problems. The Newton iteration is replaced by the use of the Steffensen method, which is also quadratically convergent, but does not require the calculation of a Jacobian nor the solution of a matrix equation. This results in a simpler and faster solution algorithm, as well as less memory usage. The method is demonstrated by solving the rate equations for impurity species and electron temperature with ionization, recombination, ohmic heating and radiative power loss as source/sink terms. A description of a 2D resistive MHD code to employ this method will be described.

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Momentum and Energy Transport due to Long-Range Collisions between Energetic Electrons*

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At the edge of an RFP, in addition to the bulk electrons $n_c(T_e \sim 25\,\mathrm{eV})$, recent measurements[1] show there is an energetic half maxwellian tail flowing parallel to the local electron current (anti-parallel to the local electric force on the electrons) with $n_H \sim .02$ to $0.1\, n_c$ and $T_H \simeq 14\, T_e$! Strong transport of parallel momentum and energy from the center must be involved. Electron plasma waves will contribute but it is proposed that a much stronger effect is due to collisions between electrons with $v_\| > v_{Te}$, the collision frequency being enhanced by the weak Debye shielding. With $\omega_{ce} > \omega_{pe}$ and f_e maxwellian, the potential surrounding such a test electron (averaged over each spherical surface or in the plane perpendicular to **B**) is

$$\Phi = -\frac{e}{r} \exp\left(-\frac{r}{\lambda_{\text{eff}}}\right) \cos kr \; , \tag{1}$$

where $k = v_{Te}/2^{1/2}\, v_\| \,\lambda_e$, $\lambda_e = (T_e/4\pi\, ne^2)^{1/2}$ and λ_{eff}, the effective Debye shielding radius, is $(2/\pi)^{1/2}(v_{Te}/v_\|)^2 \exp(+v_\|^2/v_{Te}^2)\lambda_e$. (With a non-maxwellian tail to f_e, λ_{eff} will be strongly, and k weakly, modified.) Allowing for the shear in **B**, but with uniform f_e, the operator for collisions with electrons with vel $v_\|'$ on a neighboring field line at a distance greater than ρ_e is proportional to

$$\frac{v_\|(v_\|')^2 \sin^2\gamma}{u^3}\left[f(v_\|)\,\frac{\partial f(v_\|')}{\partial v_\|^2} - \frac{\partial f(v_\|)}{\partial v_\|^2}\, f(v_\|')\right]$$

which drives f towards a half maxwellian ($\ell n\, f \sim v_\|^2$). γ is the angle between $\mathbf{v}_\|$ and $\mathbf{v}_\|'$ and $u \equiv |\mathbf{v}_\|' - \mathbf{v}_\||$.

Allowing for non-uniformity in f_e, a further part of the collision operator, after averaging, is

$$C_{\substack{\rho>\rho_e \\ \mathrm{v}_\|>\mathrm{v}_{Te}}} = -\frac{\pi\, e^4}{m^2}\frac{\partial}{\partial v_\|}\,\lambda_{\text{eff}}^2\left[f\,\frac{\partial F''}{\partial v_\|} - \frac{\partial f}{\partial v_\|}\,F''\right] \; ,$$

$$\left(F = \int 2\pi\, v_\perp\, dv_\perp\, f \quad , \quad F'' = \frac{1}{r}\frac{\partial}{\partial r} r\,\frac{\partial F}{\partial r} \; ,\right)$$

giving strong transport of parallel momentum and energy for tokamak and RFP's.

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NONLINEAR DYNAMICS OF ENERGETIC ION/ALPHA PARTICLE DESTABILIZED KINETIC ALFVÉN WAVES

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As tokamak plasmas approach reactor-relevant regimes, an understanding of the nonlinear interaction of energetic beam ions and alpha particles with the bulk plasma and the ensuing fluctuation driven losses takes on added urgency. Indeed, current designs of reactor-grade tokamaks such as ITER call for energetic parallel neutral beam heating scenarios, and alpha particles play a critical role in any burning plasma phase. As a first step towards understanding the nonlinear stage of energetic particle-induced instabilities, we consider here the nonlinear dynamics of kinetic Alfvén waves excited by energetic beam ion/alpha particles.

It is well known that shear Alfvén waves can be destabilized via resonances with energetic ions, where the destabilization coming from the expansion free energy of the energetic ion pressure.[1] Since the ratio of the mode width to the separation between mode rational surfaces scales as $|m|^{1/2}$, where m is the poloidal mode number, a multiple-helicity analysis is appropriate. We envision two possible routes for nonlinear interaction and turbulence in this system, namely through the MHD nonlinearity of the bulk plasma response and through the radial scattering of energetic particles.The nonlinear MHD interactions are similar to those encountered in driven Alfvénic turbulence. Thus, the principal interaction mechanism is via the low-frequency beat wave resonance with the MHD fluid. FLR effects characteristic of the kinetic Alfvén wave determine the difference between the spectral fluid energy (E_k) and magnetic energy ($E_m < E_k$), and thus resolve the magnitude and direction of spectral energy transfer. Results indicate that mean square flux is scattered to large scales, while fluid energy is transferred to small scales. The implication for fluctuation levels and energetic particle transport will be discussed. Secondly, since $\omega \sim k_{||} v_{hot}$, energetic ion Compton scattering is a viable interaction mechanism as well. Such scattering produces a spectral flow as well as nonlinear heating. Investigations of this process are under way and will be discussed.

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Vortex Filament Dynamics of Hydrodynamics and Magnetohydrodynamics*

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The intermittent processes associated with coherent and chaotic structure play an important role in many aspects of hydrodynamics and magnetohydrodynamics (MHD), including turbulence. Appearance of filamentary and cellular structures has been noted in experiments, computer simulations and observations. A hydrodynamical vortex filament equation known as the local induction equation is shown to be an exactly integrable soliton equation (the modified Wadati-Konno-Ichikawa equation). One and two vortex soliton solutions have been obtained by the inverse scattering method. A similar formulation of MHD vortices has been carried out with vortex filaments with two colors after the Elsasser transformation. The self and mutual interactions of filament are investigated. The system has a few invariants including energy. The internal coordinate governs the morphology of the filaments (or strings). In the studies of interaction processes of two, three, and four, we have observed three collapsing filaments of two colors or four chaotic filaments. For a system of many filaments statistical mechanics of the ensemble of filaments is also elucidated to investigate collective behaviors such as collaguration of filaments. Extension of the filament dynamics with external flows has been also undertaken.

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Theoretical Studies on the Edge Plasma Turbulence in the TEXT Experiments*

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In a slab electrostatic fluid model the ion sound effect is found to be important for the possible linearly unstable eigenmodes relevant to the TEXT edge plasma. Besides the known thermal-rippling drive, we also include the effects of impurity condensation, ionization, and charge exchange in the eigenmode analysis. Several simplified nonlinear models are examined to delineate the saturation mechanism of the linearly unstable mode. Our results are compared with the experiments on TEXT.

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3C30

MHD Stability properties expressed in terms of plasma profile characteristics.

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Experimental identification and theoretical simulation of the MHD activity in tokamaks is a major area of research. At the present time, this requires detailed and tedious computations, starting from a careful simulation of the discharge followed by extensive theoretical analysis. As a consequence this is not done very frequently and systematic analysis is generally not possible. An alternate method could involve detailed analyses of theoretical models over a wide range of parameter space, with the results catalogued in some suitable manner. This has the advantage of giving experimentalists a quick reference guide. A principal difficulty is the choice of representation of the parameter space, since the stability properties are related to both the local as well as the global characteristics of the plasma. Recently there has been a proposal to use the $s-\alpha$ diagrams to characterize the equilibrium properties[1] of experimental dischages. We examine the possibility of extending that concept to stability analysis as well. The use of $s-\alpha$ diagrams for analysis of ballooning modes is well established, here we examine their application to kink modes as well. Another method for depicting the equilibrium properties in a stability diagram is to use the inductance, l_i, and the pressure peaking factor, PPF. We will present the stability properties for a variety of plasma profiles and geometries in terms of various equilbrium quantities, including $s-\alpha$ diagrams as well as l_i , and PPF. We will also apply these concepts to experimental data from TFTR and PBXM and compare the observed MHD behaviour with the predictions of the theoretical models.
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Two Dimensional Particle Simulations of rf - Driven Plasma Sheaths *

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Two dimensional PIC simulations are performed to study sheath formation around objects immersed in a magnetized plasma, driven by intense rf waves. The parameters and the configuration are chosen to model the conditions around a Faraday screen bar, during ICRH of tokamaks. The imposed rf field can be obtained from the 3-D antenna simulation in vacuum, using ARGUS.[1] If the magnetic lines intersect the conductor, the sheath is electron depleted. For magnetic lines almost parallel to the conductor surface, ion depletion is dominant, due to larger Larmor radius. The strong field gradient in the sheath accelerates ions to impact energies sufficient to produce sputtering of the screen material. This causes impurity influx to the plasma core, and screen damage. Preliminary results show that 2-D effects are very important when the sheath thickness is comparable to the bar cross-section. Then anomalous ion transport sets in, and the ambipolar diffusion tends to re-establish quasineutrality, depleting the sheath. The possibility of opposite polarity ion and electron sheaths, across the x and y direction respectively, must be examined. In case of intense sheath formation, we observe energization of magnetized ions to energies much higher than the time-averaged rectified sheath potential. An explanation through a stochastic acceleration mechanism, triggered by the field rectification, is proposed. Existing 1-D theories[2-4] will be compared with our simulations.

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3C32

On Edge-Localized Modes

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We review the experimental properties of both giant and small edge-localized modes (ELMs). Experimental evidences suggest that giant ELMs are triggered by stronger and more extended instabilities, while small ELMs by weaker and more localized instabilities. Observing the similar appearance of both types of ELMs, we propose an edge relaxation model that qualitatively describes an ELM in three phases – triggering, edge disruption, and recovery. Quantitative models of phenomenological nature are then developed. These models exhibit burst-like solutions. Each burst is associated with a density drop, which is proportional to the repetition period of the bursts. A larger density drop corresponds to an ELM with larger H_α/D_α spikes. Giant ELMs therefore generally have longer period than small ELMs. When the edge plasmas are more stable to the triggering instability, the ELM period becomes longer. Large-amplitude ELMs can become irregular if their evolution is perturbed by background fluctuations. We also construct a specific model for small ELMs based on microtearing instabilities. For plasma parameters relevant to DIII-D edge, this model yields a repetition period for small ELMs comparable to the observed values.

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Electron Thermal Transport in High $\epsilon\beta_p$ Plasmas in TFTR †

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Recent experiments on TFTR have produced plasmas with $\epsilon\beta_p \gtrsim 1$ [1]. The electron thermal diffusivity, χ_e can be determined from equilibrium profile diagnostics processed through the interpretive code TRANSP. For shots with clean plasmas and low MHD activity χ_e can be determined both radially and temporally.

We have compared χ_e values determined in this fashion with theoretical turbulence driven values. At sufficiently high $\epsilon\beta_p$, $\epsilon\beta_p \gtrsim 0.5$, excellent agreement is found in radial and temporal behavior between the experimentally determined χ_e and theoretical predictions for resistive ballooning turbulent driven transport derived by Carreras and Diamond [2] and equally well with the predictions of Connor and Taylor [3]. (By the same token resistive ballooning driven turbulence is seen to be subdominant in low and moderate $\epsilon\beta_p$ regimes.) In the high $\epsilon\beta_p$ regime χ_e is seen to increase radially up to values of 2 to 3 m^2/sec. The strong q dependence in the theoretical resistive ballooning χ_e agrees with the observed radial dependence and predicts improved confinement when more current density is deposited into the plasma core, as is seen in the experiments. The predictions of drift wave turbulence and neoclassical MHD showed poorer agreement with the data.

In the TFTR parameter range the stabilizing effects of compressibility and FLR on resistive ballooning are small. These modes theoretically are subject to "second stability" and would be restabilized at sufficient poloidal beta.

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Boundary Larmor Radius Effect on Electrostatic Waves

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The linearized Vlasov-Poisson equations, which combine to an integro-differential equation for the perturbed electric potential, are used to investigate the kinetic effect of the plasma boundary on the stability of electrostatic waves in a homogeneous plasma slab. The Larmor motion of particles is obstructed at the plasma boundary, and this has consequences on wave propagation and stability. This phenomenon, which we call the Boundary Larmor Radius (BLR) effect, is universal for all finite plasmas. Integrating the Vlasov equation along the unperturbed orbits produces

$$f_1(\boldsymbol{x},\boldsymbol{v},t) = \frac{q}{m}\int_{\tau_b}^{0} \nabla\phi_1(\boldsymbol{x}',\tau)\cdot\frac{\partial f_0(\boldsymbol{x}',\boldsymbol{v}')}{\partial \boldsymbol{v}'}\,d\tau + f_1(\boldsymbol{x}_b,\boldsymbol{v}_b,t_b),$$

where $[\boldsymbol{x}'(\tau),\boldsymbol{v}'(\tau)]$ are the orbital coordinates, m and q are the particle mass and charge respectively, ϕ is the perturbed electric potential, f_1 is the perturbed distribution function and f_0 is the unperturbed distribution function. $f_1(\boldsymbol{x}_b,\boldsymbol{v}_b,t_b)$ is the value at the wall, a boundary condition which is needed by the Vlasov equation. Being different than the standard unperturbed orbital integral theory, our orbital integral does not always start in time from minus infinity. Instead the integration begins at an instant τ_b which is finite for orbits intersecting the wall, representing an inevitable wall interference on the particle motion. So, the introduction of this new integral limit models the BLR effect, which is usually neglected in kinetic stability analysis.

The resulting integro-differential equation is treated as an eigenvalue problem to study the BLR effect on stability. It is discretized into a matrix dispersion equation by use of the Galerkin method and then solved numerically. It is found that the ion Bernstein wave, which is undamped in an infinite homogeneous plasma, now becomes damped with a maximum damping rate of $0.35\omega_{ci}$ at r_G/L (ion Larmor radius over wall distance)≈ 0.15. In general, the damping is less pronounced at shorter perpendicular wavelengths. It seems that the BLR effect should be taken into account for sufficiently large ion Larmor radius in comparison to the characteristic dimension.

The CQL3D Fokker-Planck Model for Tokamaks

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Tail distributions must be considered for effective modeling of heating and current drive, they may be crucial for transport, and they are important to fusion processes and to several major tokamak diagnostics. CQL3D [1] is a bounce-averaged 3D Fokker-Planck code developed to explore non-Maxwellian features in tokamaks induced by dc electric fields, neutral beams (NB), and rf heating. The full 2D $p_{\parallel}, p_{\perp}$-momentum space distribution of electrons and/or ions is determined on a radial array ρ of 2D cross-section plasma flux surfaces, giving the steady-state, bounce-averaged distributions $\bar{f}(p_{\parallel}, p_{\perp}, \rho)$.

In the NB case, the source of fast ions is derived from the FREYA [2] code; current drive is obtained from the distorted ion/electron distributions, consistent with 2D equilibria obtained by iteration with the SILENE [3] code. Applications to ITER are considered. In the rf case, a bounce-averaged quasilinear module applicable to electron Landau/TTMP and cyclotron damping has been developed. Applications are considered to Asdex LHCD current profile modification experiments, using ray data passed from a Brambilla code [4]. Combined LH low and high $n_{\parallel}$-spectra give marked current profile broadening, in good agreement with the Asdex LHCD experiment [5]. This supports the concept of utilizing EC to "fill the spectral gap" for LH at intermediate plasma radii, producing versatile, spatially localized, efficient current drive. The EC ray tracing data is obtained from the TORCH [6] code. Applications to DIII–D are presented. Detailed knowledge of the distribution functions permits direct comparison with results of tail sensitive experimental detectors: hard x–ray and ECE spectra [7] are obtained.

Radial transport terms have been added to CQL3D, giving rise to a next generation plasma transport code in which the combined effects of radial transport and heating modification of the distribution functions are accounted for over transport time periods.

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