1993 International Sherwood Fusion Theory Conference

29 - 31 March, 1993 • Newport Islander Doubletree Hotel • Newport, Rhode Island

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Newport, Rhode Island

Hosted by
The MIT Plasma Fusion Center

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Hosted by

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts

Cover photograph by Jim McElholm
Courtesy of the Newport County Convention and Visitors Bureau
23 America's Cup Avenue, Newport, Rhode Island

GENERAL INFORMATION

• 228 papers were submitted, 12 of which were selected for oral presentation. In addition, there are three review papers and 4 special oral papers on Edge Physics.

• All oral papers will be presented in the Grand Ballroom. Review papers begin at 8:30 am and the invited oral papers begin at 9:30 am. A special session on Edge Physics will be presented on Tuesday afternoon from 4:00 pm to 6:00 pm.

• Poster sessions will be held in Brenton Hall, the Conference Center Exhibition Hall, on Monday from 2:00 pm to 6:00 pm, Tuesday from 8:00 pm to 10:00 pm, and Wednesday from 10:30 am to 12:30 pm.

• A Reception will be held for all attendees on Sunday evening from 7:00 pm to 9:00 pm in Grand Ballroom A.

• A Companion's breakfast will be held on Monday morning at 8:30 am in the Newport Room, on the ground floor of the main building.

• Coffee breaks will be held in the foyer of the Grand Ballroom Monday through Wednesday mornings at 9:15 am. Beer and soft drinks will be available in the Grand Ballroom foyer Monday afternoon at 3:30 pm and Tuesday evening at 9:00 pm.

• Requests for special meetings should be made at the Conference Registration Desk.

• There will be an open meeting to discuss aid to physicists from the former Soviet Union on Tuesday at 1:00 pm in the Grand Ballroom.

• Registration for the Numerical Tokamak Workshop will begin at 1:00 pm, Monday, March 29, 1993 at its own table. The Workshop will be held Wednesday afternoon and all day Thursday.

1993 International Sherwood Fusion Theory Conference
Newport Islander Doubletree Hotel, Newport, Rhode Island
March 29 - 31, 1993

Schedule

Registration - Conference Center Foyer
Sunday, March 28 - 4:00 pm - 10:00 pm
Monday, March 29 - 7:30 am - 5:00 pm
Tuesday, March 30 - 8:00 am - 5:00 pm
Wednesday, March 31 - 8:00 am - 12 noon

Oral and Poster Sessions

Review and Oral Papers - Grand Ballroom
Posters - Brenton Hall

Monday

8:20 am		Welcome	D. Sigmar, Local Chairman
8:30 - 9:20 am	1A	Review Paper	H. Wobig
9:30 - 12 noon	1B	Oral Session	(5 25-minute oral papers)
2:00 - 4:00 pm	1C	Poster Session	(55 poster papers)
4:00 - 6:00 pm	1D	Poster Session	(54 poster papers)

Tuesday

8:30 - 9:20 am	2A	Review Paper	R. D. Stambaugh
9:30 - 12 noon	2B	Oral Session	(5 25-minute oral papers)
4:00 - 6:00 pm	2S	Special Session	(Edge Physics)
8:00 - 10:00 pm	2C	Poster Session	(54 poster papers)

Wednesday

8:30 - 9:20 am	3A	Review Paper	C. E. Leith
9:30 - 10:30 am	3B	Oral Session	(2 25-minute oral papers)
10:30 - 12:30 pm	3C	Poster Session	(53 poster papers)

Coffee Service - Monday through Wednesday, 9:15 - 10:30 am
Beer and Soft Drinks - Monday, 3:30 - 4:30 pm; Tuesday, 9:00 - 10:00 pm

Monday Oral Schedule

8:20 am — D. Sigmar, Local Chairman, Opening Remarks

Review Paper
8:30 am **1A** Chair, D. Sigmar
H. Wobig, The Theoretical Basis of a Drift-Optimized Stellarator Reactor

Oral Papers 1B Chair, F. Waelbroeck

9:30 - 9:55 am	Shan, *et al.*, MHD Convection Coils and the Hartmann Number
10:00 - 10:25 am	Xu, *et al.*, Fluid Simulations of grad/Te Driven Turbulence and Transport
10:30 - 10:55 am	Finn, Stabilization of the Tearing Mode by Overlap with Driven Alfven
11:00 - 11:25 am	Hegna, *et al.*, Magnetic Islands and Their Effects in Tokamak Plasmas
11:30 - 11:55 am	Taylor, *et al.*, Shear Damping of Toroidal Drift Waves

Tuesday Oral Schedule

Review Paper
8:30 am **2A** Chair, C. Karney
R.D. Stambaugh, Edge Plasma Issues in Divertor Design Illuminated by DIII-D Results

Oral Papers 2B Chair, A. Hassam

9:30 - 9:55 am	Shapiro, *et al.*, Theory of Modulational Interaction of Trapped Ion ...
10:00 - 10:25 am	Barnes, *et al.*, Alternate Fusion - Continuous Inertial Confinement
10:30 - 10:55 am	Jones, *et al.*, Calculation of an Effective Fast Electron Diffusion Coefficient
11:00 - 11:25 am	Hammett, *et al.*, Developments in the Gyrofluid Approach to Tokamak ...
11:30 - 11:55 am	Candy, *et al.*, Alpha-particle -driven Nonideal Toroidal Alfven Eigenmodes

Special Papers 2S Chair, H. Weitzner, Special Session - Edge Physics

4:00 - 4:25 pm	Hinton, The Radial Electric Field Near a Separatrix in Diverted Tokamaks
4:30 - 4:55 pm	Braams, Numerical Models for the Edge Plasma
5:00 - 5:25 pm	Cohen, Turbulence in Tokamak Scrape-off Layers
5:30 - 5:55 pm	Weitzner, A Survey of Problems in Divertor and Edge-Plasma Theory

Wednesday Oral Papers

Review Paper 3A Chair, P. Terry
8:30 - 9:20 am C.E. Leith, Numerical Models of Weather and Climate

Oral Papers 3B Chair, A. Lipschitz

9:30 - 9:55 am	Betti, *et al.*, Destabilization of the Internal Kink by Energetic-Circulating Ions
10:00 - 10:25 am	Sykes, *et al.*, Tight Aspect-Ratio Tokamaks: Theory and Experiment

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March 28 - 31, 1993

REGISTRATION - Newport Islander Doubletree Conference Center
Sunday, March 28 - 4:00pm - 10:00pm
Monday, March 29 - 7:30am - 5:00pm
Tuesday, March 30 - 8:00am - 5:00pm
Wednesday, March 31 - 8:00am - noon

MONDAY MORNING

WELCOME - 8:20am - Dieter Sigmar, Local Chairman

1A Review Talk
8:30am - 9:20am
Presiding: D. Sigmar

1A1. The Theoretical Basis of a Drift-Optimized Stellarator Reactor. H. Wobig.

1B ORAL SESSION
9:30am - 12:00pm
Presiding: F. Waelbroeck

1B1. MHD Convection Cells and the Hartmann Number. X. Shan and D. Montgomery.
1B2. Fluid Simulations of grad/Te Driven Turbulence and Transport in Boundary Plasmas. X. Q. Xu and R. H. Cohen.
1B3. Stabilization of the Tearing Mode by Overlap with Driven Alfven Resonance Islands. J. M. Finn.
1B4. Magnetic Islands and Their Effects in Tokamak Plasmas. C. C. Hegna, J. D. Callen, T. A. Gianakon, W. X. Qu, A. I. Smolyakov, and J. P. Wang.
1B5. Shear Damping of Toroidal Drift Waves. J. B. Taylor, J. W. Connor, and H. R. Wilson.

MONDAY AFTERNOON

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

1C1. How to Make a heliotron into a Helias like a Heliac for Reactor Studies. P. R. Garabedian.
1C2. ASPAN: Advanced Spectral Analysis of TFTR Microwave Scattering. A. Sidorenko, K. S. Riedel, N. Bretz, R. Nazikian, and D. J. Thomson.
1C3. Kinetic Ballooning Stability of Experimental Parameters Including Shear Flow and Equilibrium Gradients. M. Kotschenreuther.

1C4. Kinetic Effects on TAE and KTAE Modes. C. Z. Cheng and G. Y. Fu.
1C5. (Nearly) Portable PIC Code for Parallel Computers. V. K. Decyk.
1C6. Statistical and Transport Analysis Using the MFE Database. J. C. Wiley, P. M. Valanju, W. H. Miner, Jr., P. N. Yushmanov, and D. W. Ross.
1C7. Far Field ICRF Sheath Formation on Walls and Limiters. J. R. Myra and D. A. D'Ippolito.
1C8. Coherent Drift Wave Structures in Sheared Magnetic Fields. P. J. Morrison and W. Horton.
1C9. Plasma Polarization and Tokamak Space Charge. R. D. Hazeltine, E. R. Solano, and P. M. Valanju.
1C10. Conformal Magnetosonic Waves. S. V. Bulanov and F. Pegoraro.
1C11. Application of the Realizable Markovian Closure to a Two-Field Model of Dissipative Drift-Wave Turbulence. J. C. Bowman and J. A. Krommes.
1C12. Stability of Toroidal Alfven Eigenmodes Using an Initial Value Hybrid Code. G. Vlad, S. Briguglio, C. Kar, F. Zonca, and F. Romanelli.
1C13. Self-Similar Transport. D. Stevens, H. Weitzner, and G. M. Zaslavsky.
1C14. Resistive Ballooning Modes Revisted. S. V. Novakovskii, P. N. Guzdar, J. F. Drake, C. S. Liu, and F. L. Waelbroeck.
1C15. Global Wave Modeling of Electron Interactions with Fast Magnetosonic Waves. E. F. Jaeger, D. B. Batchelor, and M. Murakami.
1C16. Nonlinear Damping of Drift Waves by Strong Flow Curvature. K. L. Sidikman, B. A. Carreras, L. Garcia, and P. H. Diamond.
1C17. 2D nonlinear Dynamics of Four Driven Vortices. A. V. Rogalsky, P. N. Guzdar, J. M. Finn, and J. F. Drake.
1C18. Hamiltonian Attractors and Iso-Topological Relaxation in Reduced Magnetohydrodynamics. M. Isichenko and A. V. Gruzinov.
1C19. Theoretical Analysis of the Emissions at the Cyclotron Frequency Harmonics of Fusion Produced Alpha Particles. N. R. Asherie and B. Coppi.
1C20. Local Shear in General Magnetic Stellarator Geometry. R. E. Waltz and A. H. Boozer.
1C21. Investigation of the Effect of External Magnetic Perturbations Upon Divertor Heat Load. B. J. Braams and M. D. Teytel.
1C22. Feedback Control of Tokamak Instabilities. A. K. Sen.
1C23. Alpha Heating Predictions for DT Supershots. R. V. Budny, M. G. Bell, Z. Chang, E. Fredrickson, H. Park, J. D. Strachan, and S. J. Zweben.
1C24. Instantaneous Phase-Space Lyapunov Expansion Rates in Coulombic Many-Body Systems. D. M. Barnett and T. Tajima.
1C25. Gyrokinetic i(delta) Particle Model of Dissipative Trapped Electron Mode Turbulence. J-N. Leboeuf and R. D. Sydora.
1C26. Transport Simulation of Advanced Tokamak Operations. V. S. Chan, Y. R. Lin-Liu, L. L. Lao, H. St John, T. S. Taylor, and A. D. Turnbull.
1C27. 3D MHD Simulations of Helicity Injection for Fluctuation Suppression in RFP's. C. R. Sovinec, S. C. Prager, and Y. L. Ho.
1C28. Multi-Species, Two-Velocity, One-Space Fokker-Planck Code. D. P. Coster.
1C29. Coupling Transport Fluid Codes in 1D and 2D. A. Tarditi, R. H. Cohen, and T. D. Rognlien.
1C30. Nonfully Developed Saturated States in the Microtearing Model for Magnetic Edge Turbulence. P. W. Terry, D. E. Newman, and E. Fernandez.
1C31. Estimating Tokamak Plasma Transport Scaling via Gyrokinetic Particle Simulation. R. A. Santoro and W. W. Lee.
1C32. Current Driven Ballooning Modes in High-q(o), High-beta(p) Tokamaks. J. J. Ramos.
1C33. Nonlinear Studies of Vortex Dynamics in Non-Neutral Plasmas. A. Y. Aydemir.
1C34. Diffraction Corrections to Ray Propagation in a Magnetized Plasma. R. E. Aamodt.
1C35. Dual Cascade and Minimum Enstrophy State in the Tokamak Scrape-Off Layer. N. Mattor, R. H. Cohen, and X. Q. Xu.
1C36. Exploration of Stellarator Orbit Topology Using J**. J. A. Rome.

1C37. Plasma Potentials Generated by Microwaves Incident on a Magnetic Gradient: Theory and Computer Simulation. R. F. Post and D. J. Larson.
1C38. A Toroidal Gyrokinetic Poisson Solver. J. Li, W. W. Lee, and S. E. Parker.
1C39. Charged-Particle Stopping Powers in Inertial Confinement Fusion Plasmas. R. D. Petrasso and C-K. Li.
1C40. Nonlinear Two Fluid Theory of Propagating Magnetic Structures. T. J. Schep, F. Pegoraro, and J. Rem.
1C41. Low-Frequency Short-Wave-Length Electromagnetic Fluctuations in a Plasma and Anomalous Heat Conductivity. M. O. Vakoulenko.
1C42. Parallel Deposition, Sorting, and Reordering Methods in the Hybrid Ordered Plasma Simulation (HOPS) Code. D. V. Anderson and D. E. Shumaker.
1C43. Local Ideal Stability of Realistic Field-Reversed Configuration (FRC) Equilibria. L. C. Steinhauer.
1C44. Changes in the Tokamak Current During MHD Activity. A. H. Boozer.
1C45. Numerical Simulation of Drift Turbulence in the Presence of Sheared Flows Parallel and Perpendicular to the Magnetic Field. X. N. Su, W. Horton, and J. Q. Dong.
1C46. Non Linear Drift Wave Turbulence. X. Garbet, L. Laurent, and A. Samain.
1C47. Global Alpha-Alfven Wave Dispersion Relation and Rosetta Stone. C. L. Hedrick, J-N. Leboeuf, and D. A. Spong.
1C48. Vorticity Model of MHD Jets and Conservation of Canonical Circulation. P. M. Bellan.
1C49. Nonlinear Mode Conversion. L. Friedland, A. N. Kaufman, and J. J. Morehead.
1C50. Convective Momentum Transport, Shock Viscosity, and the L-H Transition in Tokamaks. C. E. Crume, Jr., K. C. Shaing, and C. T. Hsu.
1C51. Nonlinear Formalism for Plasma Turbulence Characterized by Two Different Scale Lengths. E. K. Maschke.
1C52. Magnetic Field Effects on Ballooning Modes in Classical Fluids. E. Hameiri and A. Lifschitz.
1C53. Onset of the Sawtooth Crash. F. L. Waelbroeck.
1C54. Partially Linearized Gyrokinetic Simulations with Ion-Ion Collisions. B. I. Cohen, A. M. Dimits, and T. B. Kaiser.
1C55. Stochastic Ripple Losses of Fast Ions on TFTR. M. H. Redi, M. C. Zarnstorff, R. B. White, and R. J. Goldston.

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

1D1. Bulk Ion Gyrokinetic Effect in the 3D Hybrid Particle/Fluid Code, MH3D-K. W. Park, G. Y. Fu, L. E. Sugiyama, W. W. Lee, D. Monticello, and S. E. Parker.
1D2. An Explanation for the Cause and Energy Source of Solar Flare Production - A New Mechanism of Thermonuclear Reaction. H-Z. Wang and G-Q. Wang.
1D3. Exceeding the Brillouin Limit: A Novel Path to Inertial-Electrostatic Confinement of a Single-Species Plasma. L. Turner and D. C. Barnes.
1D4. Symbolic Signal Processing. A. B. Rechester and R. B. White.
1D5. Two-Dimensional Numerical Simulation of Drift Waves and Trapped Ion Modes. O. T. Kingsbury and R. E. Waltz.
1D6. On Magnetohydrodynamic Modes Driven by Energetic Particles in Tokamaks. L. Chen, S. T. Tsai, and F. Zonca.
1D7. An Analytically-Based Method for Rapid Evaluation of MeV Ion Loss in Tokamaks with Low-n Perturbations. H. E. Mynick.
1D8. Eikonal Theory of Gyroresonant Case-van Kampen Modes in Tokamak Geometry. E. R. Tracy, A. N. Kaufman, A. J. Brizard, and D. R. Cook.
1D9. Anomalous Perturbative Transport in Tokamaks due to Drift-Wave Turbulence. A. A. Thoul, P. L. Similon, and R. N. Sudan.
1D10. Neutral-Plasma Interaction in the Long Mean-Free-Path Limit. M. D. Calvin, R. D. Hazeltine, and P. M. Valanju.

1D11. Self-Consistent Theory of Magnetic Diffusion and the Turbulent Dynamo. A. V. Gruzinov and P. H. Diamond.
1D12. A 3D Fokker-Planck Code for Studying Transport Along the Magnetic Field Lines. O. Sauter, R. W. Harvey, and M. G. McCoy.
1D13. The VH-mode at JET. D. P. O'Brien, B. Balet, N. Deliyanakis, C. M. Greenfield, and P. M. Stubberfield.
1D14. Stationary 3D Vlasov Plasma Equilibria. D. R. Martin and D. V. Anderson.
1D15. Neoclassical Kinetic Theory Near the Edge of a Diverted Tokamak Plasma. E. R. Solano and R. D. Hazeltine.
1D16. 3-D Monte Carlo Simulations of Fast Ion Confinement for Stellarators with the Radial Electric Field. K. Hanatani.
1D17. Feasibility of Driving Perpendicular Rotation in Core Plasma by Off-Axis Neutral Beam Injection to Suppress Microturbulence. A. B. Hassam.
1D18. The H Confinement Regime as a State of Topological Incompatibility with Transport Inducing Normal Modes. B. Basu and B. Coppi.
1D19. Time-Advance Algorithms Based on Hamilton's Principle. H. R. Lewis and P. J. Kostelec.
1D20. DT Simulation of ICRF Heated Supershots in TFTR using TRANSP. R. C. Goldfinger, D. B. Batchelor, C. K. Phillips, R. V. Budny, G. W. Hammett, J. C. Hosea, D. M. McCune, J. E. Stevens, J. R. Wilson, and Team. TFTR.
1D21. Dynamics and Control of m=2 Islands in TEXT. X. H. Wang, A. Bhattacharjee, D. D. Schnack, D. C. Sing, A. J. Wootton, M. E. Austin, D. L. Brower, J. Y. Chen, R. F. Gandy, and C. X. Xu.
1D22. Diffraction and Gaussian n(parallel) Effects in Lower Hybrid Wave Propagation in Tokamaks. L. Vahala and G. Vahala.
1D23. Finite Mean-Free-Path Effects in Tokamak Scrape-Off Layers. R. H. Cohen, T. D. Rognlien, X. Q. Xu, I. B. Bernstein, and Q. Chen.
1D24. Simulating Density and Temperature Modulation in Oscillating Gas Puff Experiments. D. W. Ross, B. Richards, and J. C. Wiley.
1D25. Reconnection of Magnetic Field Lines in a Turbulent Flow. R. G. Kleva.
1D26. Lower Hybrid Current Drive in the Presence of ICRF Waves. A. K. Ram, A. Bers, and V. Fuchs.
1D27. Range of Objectives of the Ignitor Experiment. M. Nassi, B. Coppi, P. Detragiache, and L. E. Sugiyama.
1D28. RF Enhanced Bootstrap Current with CQL3D. R. W. Harvey, M. G. McCoy, P. A. Politzer, V. S. Chan, and K. Kupfer.
1D29. Effects of Ion Diamagnetic Flow on Shock Formation in Poloidally rotating Tokamak Plasmas. K. C. Shaing and C. T. Hsu.
1D30. Trapped-Particle Effects in the Nonlinear Evolution of Magnetic Islands. J. D. Callen, A. I. Smolyakov, and C. C. Hegna.
1D31. Finite Banana Orbit Effects in the Presence of Mini-Magnetic Islands. J. P. Wang, C. C. Hegna, and J. D. Callen.
1D32. Simulations of interacting Bootstrap-Current-Driven Magnetic Islands. T. A. Gianakon, C. C. Hegna, and J. D. Callen.
1D33. Diverting Alpha-Particle Power to Tail Ions in a Reactor. N. J. Fisch and J-M. Rax.
1D34. Radial Transport and the Dynamics of the Transition to Neutralizer Regimes in Gas-Fueled Divertors. R. T. Ratt, A. V. Gruzinov, P. H. Diamond, A. E. Koniges, and G. G. Craddock.
1D35. Modeling the ICRF-Edge Interaction in H-Modes. D. A. D'Ippolito, J. R. Myra, J. Jacquinot, and M. Bures.
1D36. Effect of Clumps on the Frequency Spectrum of Trapped Electron Driven Drift Wave Turbulence. A. S. Ware and P. W. Terry.
1D37. Three-Dimensional Field Solution for the Quiet Implicit PIC Method. R. A. Nebel and D. C. Barnes.
1D38. On the FLR Stabilization of High Poloidal Mode Number External Kinks. S. Migliuolo, B. Rogers, and B. Coppi.
1D39. The Effect of an Axial Current on Particle Loss Cone in an Axially Symmetric Mirror. S. Ma, J. M. Dawson, and W. J. Nunan.

1D40. Toroidal Drift Waves with an Equilibrium Velocity Field. S. Sen.
1D41. Anomalous Momentum Transport from Drift Waves. R. R. Dominguez and G. M. Staebler.
1D42. Resonance Parallel Viscosity in the Banana Regime in Poloidally Rotating Tokamak Plasmas. N. Dominquez, K. C. Shaing, and C. T. Hsu.
1D43. Reconstruction of Ideal MHD Equilibria with Anisotropic Pressure and Aximuthal Mass Flow from Measurements. L. Bai and M. E. Mauel.
1D44. Shear Flow Generation by Reynolds Stress and Suppression of Resistive g Modes. H. Sugama and W. Horton.
1D45. A Transmission/Escape Probabilities Model for Neutral Particle Transport in the Outer Regions of a Diverted Tokamak. W. M. Stacey.
1D46. Nonlinear Evolution of Alpha-Particle-Driven Alfven Turbulence and Associated Transport. F. Wising, F. Y. Gang, and D. J. Sigmar.
1D47. Ultra High Beta Transport and Stability. S. C. Cowley.
1D48. A Study of the Guiding Center Approximation. Q. Yao and A. H. Boozer.
1D49. Plasma Transport in Mixed Magnetic Topologies. C. C. Hegna and J. D. Callen.
1D50. Radiative Divertor Simulations. M. E. Rensink, S. L. Allen, D. N. Hill, T. B. Kaiser, and T. D. Rognlien.
1D51. The Neumann Problem in Toroidal Domains Solved by an Integral Equation Technique for the Surface Current. P. Merkel.
1D52. Parallel Flow Gradient Driven Instability. L. A. Charlton, B. A. Carreras, and P. H. Diamond.
1D53. Radial Diffusion of a Minority Species in a Tokamak due to ICRH. L. Vacca.
1D54. A Comparison of the Two-Fluid m=1 Stability Criterion to Sawtooth Behavior in TFTR. L. Zakharov, S. Migliuolo, and B. Rogers.

TUESDAY MORNING

2A Review Talk
8:30am - 9:20am
Presiding: C. Karney

2A1. Edge Plasma Issues in Divertor Design Illuminated by DIII-D Results. R. D. Stambaugh.

2B ORAL SESSION
9:30am - 12:00pm
Presiding: A. Hassam

2B1. Theory of Modulational Interaction of Trapped Ion Convective Cells and Drift Wave Turbulence. V. D. Shapiro, P. H. Diamond, V. Lebedev, G. Soloviev, and V. Shevchanko.
2B2. Alternate Fusion - Continuous Inertial Confinement. D. C. Barnes, L. Turner, and R. A. Nebel.
2B3. Calculation of an Effective Fast Electron Diffusion Coefficient from 2-D Hard X-ray Images from PBX-M. S. E. Jones, S. Bernabei, R. Kaita, J. Kesner, S. Luckhardt, F. Rimini, and S. Von Goeler.
2B4. Developments in the Gyrofluid Approach to Tokamak Turbulence Simulations. G. W. Hammett, M. A. Beer, W. Dorland, S. C. Cowley, and S. A. Smith.
2B5. Alpha-Particle-Driven Nonideal Toroidal Alfven Eigenmodes. J. Candy and M. N. Rosenbluth.

TUESDAY AFTERNOON

2S SPECIAL SESSION – EDGE PHYSICS
4:00-6:00pm
Presiding: H. Weitzner

2S1. The Radial Electric Field Near a Separatrix in Diverted Tokamaks. F. L. Hinton.
2S2. Numerical Models for the Edge Plasma. B. J. Braams.
2S3. Turbulence in Tokamak Scrape-Off Layers. R. H. Cohen.
2S4. A Survey of Problems in Divertor and Edge Plasma Theory. H. Weitzner.

TUESDAY EVENING

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

2C1. Divertor Target Geometry Effects on Tokamak Edge Plasmas. M. S. Day, F. Najmabadi, and R. W. Conn.
2C2. An Investigation of the Large Growth Rate Limit of Tearing Modes. J. M. Greene and R. L. Miller.
2C3. Origin of Radiation Emission Induced by Fusion Produced Products. B. Coppi and N. R. Asherie.
2C4. Computer Simulation of Transport Driven Current in Tokamaks. W. J. Nunan and J. M. Dawson.
2C5. Gyrokinetic Simulation in a General Metric. M. J. LeBrun and T. Tajima.
2C6. Influence of Trapped Thermal Particles on Global n=1 Modes in High Temperature Tokamak Plasmas. T. M. Antonsen, Jr. and A. Bondeson.
2C7. Identification and Solution of the Generic Linear Mode Conversion Problem in One Dimension. W. G. Flynn and R. G. Littlejohn.
2C8. A Generic Coordinate System and a Set of Generic Variables for the MFE Database. W. H. Miner, Jr., D. W. Ross, E. R. Solano, P. M. Valanju, and J. C. Wiley.
2C9. Three Religious Rules of Nonlinear Physics. V. V. Yankov.
2C10. Non-Vanishing Fast-Ion Bootstrap Current on Axis. R. P. Gormley, C. T. Hsu, and D. J. Sigmar.
2C11. Bootstrap Current of Transition Particles. S. G. Shasharina, P. N. Yushmanov, and J. R. Cary.
2C12. Visualization Strategies in Tokamak Fluid Turbulence Studies. G. D. Kerbel and R. E. Waltz.
2C13. Quasistatically Evolved Toroidal Equilibria. J. A. Crotinger, S. W. Haney, L. L. LoDestro, and L. D. Pearlstein.
2C14. Neoclassical Theory of Poloidal and Toroidal Rotations. A. A. Galeev, A. B. Hassam, C. S. Liu, and R. Z. Sagdeev.
2C15. Dynamics of Fluid Models for Collisional and Collisionless Drift-Wave Turbulence. G. G. Craddock, A. E. Koniges, J. A. Crotinger, P. H. Diamond, D. E. Newman, and P. W. Terry.
2C16. Atomic Physics Modifications of Braginskii for Divertor and Edge Plasmas in Tokamaks. P. J. Catto.
2C17. Simulation of Radiative Divertor Flame Fronts and Supersonic Flow. R. B. Campbell, D. A. Knoll, and P. R. McHugh.
2C18. Stochasticity and Reconnection in an Area Preserving Nontwist Map. D. Del-Castillo-Negrete and P. J. Morrison.
2C19. The Role of Self-Consistent Lagrangian Chaos in Benard and Interchange Convection. K. Hermiz and J. M. Finn.
2C20. Beam and Impurity Effects on the Ion Temperature Gradient Mode. J. Q. Dong, J. Y. Kim, and W. Horton.
2C21. What is Thermodynamic Equilibrium for a Non-Neutral Plasma in a DC Magnetic Field. H. Chen and D. Montgomery.

2C22. Isotope Effect and Charge-Exchange Energy Loss. P. M. Valanju, R. D. Hazeltine, and M. D. Calvin.
2C23. Ponderomotive Force Induced by Wave Absorption. V. I. Krivenski.
2C24. Inertial-Electrostatic Confinement Studies. T. N. Tiouririne, R. A. Nebel, L. Turner, W. D. Nystrom, R. W. Bussard, G. H. Miley, Y. Yamamoto, J. Bates, and H. R. Lewis.
2C25. 3D Toroidal Gyrokinetic Simulation of ITG Driven Turbulence. S. E. Parker, W. W. Lee, and R. A. Santoro.
2C26. Ballooning Modes in Linked Mirror Configurations. H. V. Wong, H. L. Berk, V. I. Ilgisonis, and V. P. Pastukhov.
2C27. Arbitrary Mode Number Boundary Layer Theory for Non-Ideal Toroidal Alfven Modes. H. L. Berk, R. R. Mett, and D. M. Lindberg.
2C28. Instability due to Axial Shear and Surface Impedance. Y. Tsidulko, H. L. Berk, and R. H. Cohen.
2C29. Solution of the Drift-Kinetic Equation for Global Plasma Modes and finite Particle Orbit Widths. F. Porcelli, R. Stankiewicz, W. Kerner, and H. L. Berk.
2C30. Gyrokinetic Simulations in Toroidal Geometry. A. M. Dimits and J. A. Byers.
2C31. Finite Beta Induced Gaps in the Toroidal Alfven Spectrum. M. S. Chu, W. W. Heidbrink, E. J. Strait, and A. D. Turnbull.
2C32. Anomalous Energy Pinch in Turbulent Transport. A. I. Smolyakov and J. D. Callen.
2C33. Anomalous Electron Streaming due to Electrostatic Modes in Tokamak Plasmas. S. D. Schultz, A. Bers, and A. K. Ram.
2C34. Nonlinear Gyrofluid Simulation and Analysis: ITG Turbulence. W. Dorland, G. W. Hammett, M. A. Beer, and T. S. Hahm.
2C35. Thermal Runaway Due to Fast Ion Friction Driven Heat Pinch. Y.-B. Kim and F. L. Hinton.
2C36. Monte-Carlo Simulation Studies of Effects of Radial Electric Field on Particle Motion in the Tokamak Plasma. H. Xiao, Y. Z. Zhang, H. Ye, R. D. Hazeltine, and P. M. Valanju.
2C37. Effects of Rational Surface Density on Resistive g Turbulence. A. D. Beklemishev, H. Sugama, and W. Horton.
2C38. Bootstrap Current Induced by Neutral Beam Injection. C. T. Hsu, K. C. Shaing, R. P. Gormley, and D. J. Sigmar.
2C39. Shear Flow Generation and Turbulence Suppression by Resistive Ballooning and Resistive Interchange Modes. P. N. Guzdar and J. F. Drake.
2C40. Tearing Mode Stability in Tokamaks with Shaped Plasma Cross-Sections. R. Fitzpatrick, R. J. Hastie, T. J. Martin, and C. M. Roach.
2C41. Space-Time Statistics of Drift Wave Turbulence. W. Horton.
2C42. Increasing the Capabilities of Preische's Post-Processor for PEST. J. L. Johnson, J. Manickam, and M. S. Chance.
2C43. A Model of Energy Transport Based on Alfven-Wave Filaments. G. J. Morales.
2C44. Distributed Plasma Simulation Using C++ and ESP. G. Furnish and M. G. Gray.
2C45. Onsager Symmetries for Nonequilibrium Steady States. J. A. Krommes and G. Hu.
2C46. The Transport of Toroidal Momentum in TFTR Plasmas and Relevant Collective Modes. D. R. Ernst, B. Coppi, S. D. Scott, and Team. TFTR.
2C47. The Reconstruction of Equilibrium in TFTR with use of EMEQ Code. N. Pomphrey and L. Zakharov.
2C48. Differential Algebraic Plasma Simulation. J. Koga and T. Tajima.
2C49. Energetic Particle Drive for TAE and Kinetic TAE Modes in a Low-Shear Tokamak. S. E. Sharapov and B. N. Breizman.
2C50. On the Relationship Between Marfes and Density Limits. J. P. Freidberg, J. A. Wesson, and C. Kurz.
2C51. Quench Protection in Superconducting Magnets. A. Shajii and J. P. Freidberg.
2C52. Smoothing Spline Analysis of Plasma Profiles. K. Imre and K. S. Riedel.
2C53. Calculations in the Tokamak Vacuum Region: Delta W(v) and Diagnostic Capabilities. M. S. Chance.
2C54. The Magnetohydrodynamic Clump Instability in Tokamaks. Y. Yuan and A. Bhattacharjee.

WEDNESDAY MORNING

3A Review Talk
8:30am - 9:20am
Presiding: P. Terry

3A1. Numerical Models of Weather and Climate. C. E. Leith.

3B ORAL SESSION
9:30am - 10:30am
Presiding: A. Lifschitz

3B1. Destabilization of the Internal Kink by Energetic-Circulating Ions. R. Betti and J. P. Freidberg.
3B2. Tight Aspect-Ratio Tokamaks: Theory and Experiment. A. Sykes, J. W. Connor, R. Duck, K. Gibson, M. Gryaznevich, T. C. Hender, J. Hugill, D. C. Robinson, M. F. Turner, M. Walsh, and H. R. Wilson.

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

3C1. Influence of Local Density and Temperature Gradients on Internal Modes in High Temperature Plasmas. P. Detragiache.
3C2. A Comparison of the Performance of a Fluid Code on the C90 and the iPSC/860. V. E. Lynch, B. A. Carreras, B. Curtis, J. B. Drake, and J-N. Leboeuf.
3C3. Fluid Equations for Plasmas with a Strong Radial Electric Field and Steady Flow. C. S. Chang and H. R. Strauss.
3C4. Effects of Flux Surface Jitter on Electrostatic Drift Waves. M. G. Prahovic, A. Y. Aydemir, and R. D. Hazeltine.
3C5. Nonlinear Gyrofluid Simulations of Toroidal ITG Turbulence. M. A. Beer, G. W. Hammett, W. Dorland, and S. C. Cowley.
3C6. A Moving Finite Element Model of the Tokamak Scrapeoff Region. A. H. Glasser and A. P. Kuprat.
3C7. A Moving Finite Element Model of the Incompressible Kelvin-Helmholtz Instability. A. P. Kuprat and A. H. Glasser.
3C8. Nonlinear Gyrofluid Models of Shear Alfven Instabilities in Ignited and Beam Heated Toroidal Plasmas. D. A. Spong, C. L. Hedrick, and B. A. Carreras.
3C9. A Fokker-Planck Equation for Moderately Coupled Plasmas. C-K. Li and R. D. Petrasso.
3C10. Radial Electric Field Influence on the Neoçlassical Orbits in Tokamaks. S. I. Krasheninnikov and P. N. Yushmanov.
3C11. Symmetry Groups and Solutions of Plasma Fluid Models. R. Acevedo and P. J. Morrison.
3C12. Ideal MHD Analysis of Advanced Regime Tokamaks. J. Manickam and A. Bondeson.
3C13. Fuel and Helium Confinement in Fusion Reactors. W. A. Houlberg and S. E. Attenberger.
3C14. Neoclassical Tearing Dynamo and Self-Sustainment of a Bootstrapped Tokamak. A. Bhattacharjee and Y. Yuan.
3C15. Unification of Fully Implicit Fluid Edge-Plasma Transport Codes. T. D. Rognlien, R. B. Campbell, T. B. Kaiser, D. A. Knoll, P. R. McHugh, J. L. Milovich, M. E. Rensink, and G. R. Smith.
3C16. Stability Threshold of TAE Modes. G. Y. Fu and C. Z. Cheng.
3C17. Fast Ion Physics Related to Cyclotron Emission. K-R. Chen.

3C18. Kinetic Simulation of eta(i) Modes and Transport in Tokamaks. M. G. Gray, M. J. LeBrun, T. Tajima, G. Furnish, Y. Kishimoto, and W. Horton.
3C19. Poloidal Flow Generation in the Evolution of Trapped Electron Drift Instabilities in the Collisionless and Semicollisional Regime. R. D. Sydora and J. M. Dawson.
3C20. Neoclassical Rotation of Impure Plasma in Tokamaks. C. S. Liu and S. V. Novakovskii.
3C21. Divertor Design Study Using LEDGE and DEGAS. T. B. Kaiser, M. E. Rensink, T. D. Rognlien, and D. N. Hill.
3C22. Lower Hybrid Current Drive in Shaped Tokamaks. J. Kesner.
3C23. Anomalous Sources of Radial Electric Fields in Tokamaks. V. Smerdyakov, N. Mattor, and P. H. Diamond.
3C24. Edge Turbulence from the Tokamak Core. I. Raskolnikov, N. Mattor, and P. H. Diamond.
3C25. Optimized Parallel Convolutions for Non-Linear Fluid Models of Tokamak (eta i) Turbulence. J. L. Milovich, G. Tomaschke, and G. D. Kerbel.
3C26. Three Dimensional Simulations of the Parallel Velocity Shear Instability. D. R. McCarthy, J. F. Drake, and P. N. Guzdar.
3C27. Kinetic Treatment of Magnetosonic Wave Reflection by Minority Gyroresonant Ballistic Waves in Tokamak Geometry. A. N. Kaufman, A. J. Brizard, and D. R. Cook.
3C28. Progress in Triangular Magnetohydrodynamics. D. D. Schnack and Z. Mikic.
3C29. Numerical Simulation of Bootstrap Current. Y. Wu and R. B. White.
3C30. Nonlinear Dynamics of the m=1 Instability and Fast Sawtooth Collapse in High-Temperature Plasmas. X. Wang and A. Bhattacharjee.
3C31. Numerical Investigation of the Ion-Temperature-Gradient Stability of DII-D Plasmas in Various Modes of Energy Confinement. A. J. Brizard, J. Fitzpatrick, T. K. Fowler, X. Q. Xu, K. H. Burrell, and T. H. Osborne.
3C32. m=1 Resistive Internal Reconnection in a Two Fluid Approximation. L. E. Sugiyama and W. Park.
3C33. Neutral Gas Transport Modeling with DEGAS 2. C. Karney and D. Stotler.
3C34. Fastwac for full Wave Current Drive Calculations. P. E. Moroz.
3C35. Modelling of Ultra High Recycling Divertors with the PLANET-TD Code. M. Petravic and G. Bateman.
3C36. Fast Wave Flow Drive in a Two-Ion-Component Plasma. F. Y. Gang and D. J. Sigmar.
3C37. Resonant Interaction of Alphas with TAE-Modes. B. N. Breizman, C. T. Hsu, and D. J. Sigmar.
3C38. Instability near the Minority Ion Cyclotron Resonance. D. A. Russell, R. E. Aamodt, and C. N. Lashmore-Davies.
3C39. MHD Simulation on an Unstructured Mesh. H. R. Strauss and D. W. Longcope.
3C40. An Analytical Model of Coupled Fluctuation and Flow Dynamics in Self-Regulating Turbulence. P. H. Diamond, Y. Liang, and B. A. Carreras.
3C41. Dynamo and Diffusion Processes in a Reversed Field Pinch. T. Amano and A. Nagata.
3C42. Effective Resistivity and Heat Conduction in a Stochastic Magnetic Field. Ph. Ghendrih, H. Capes, F. Nguyen, and A. Samain.
3C43. Wave Kinetic Description of Lower-Hybrid Absorption in Tokamaks. K. Kupfer, D. Moreau, and X. Litaudon.
3C44. Model for ICRF Fast Wave Current Drive in Self-Consistent MHD Equilibria. P. T. Bonoli, R. C. Englade, M. Porkolab, and M. E. Fenstermacher.
3C45. Parallel Computation and the Basis System. G. R. Smith.
3C46. Microinstability Studies of Advanced Tokamak Configurations. G. Rewoldt and W. M. Tang.
3C47. A New Interpretation of the Ballooning Mode Representation Formalism. J. Y. Kim.
3C48. MHD Properties of Advanced Plasma Configurations. S. C. Jardin, C. Kessel, J. Manickam, D. Monticello, W. Nevins, W. Park, J. J. Ramos, A. Reiman, L. Zakharov, and C. Wang.
3C49. Neoclassical MHD Modified Eigenmode Equations for Internal Kink Modes in Tokamak Plasmas. Q. X. Qu and J. D. Callen.
3C50. The Importance of Three-Dimensional Effects for Antenna Modeling. M. D. Carter, D. B. Batchelor, and D. C. Stallings.
3C51. Plasma Energy for Electromagnetic Perturbations. B. A. Shadwick and P. J. Morrison.
3C52. Alfven-wave Current Drive and Magnetic Field Stochasticity. C. Litwin and C. C. Hegna.

3C53. Two-Dimensional Eigenmode Analysis of Long-Wavelength Microinstabilities in Rotating Asisymmetric Plasmas. M. Artun, W. M. Tang, and G. Rewoldt.

The theoretical basis of a drift-optimized stellarator reactor

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The stellarator is a 3-dimensional toroidal configuration without induced toroidal plasma currents. The confining magnetic field is generated by external coils only thus making stationary reactor operation possible. In order to yield a viable reactor concept this coil system must be optimized with respect for its technical feasibility and plasma performance. At the IPP-Garching, these activities have led to the Helias concept, where by proper choice of the magnetic field configuration the currents flowing in the plasma can be reduced to a low level so that the currents parallel to the magnetic field (Pfirsch-Schlüter currents) become smaller than the diamagnetic currents. As a consequence the radial shift of the plasma column with rising plasma pressure (Shafranov shift) is strongly reduced and the MHD-stability limit raised to values around $\bar{\beta} \approx 5\%$. In essence the conditions for an optimised reactor configuration are

- Good magnetic surfaces of the vacuum field without major resonances, islands and stochastic regions.
- Low Shafranov shift and a stiff equilibrium configuration up to $\bar{\beta} = 5\%$.
- MHD-stability up to $\bar{\beta} \approx 5\%$.
- Sufficiently small neoclassical plasma losses so that the ignition condition is satisfied.
- Sufficiently small bootstrap currents so that the magnetic field is not modified by this effect.
- Good confinement of α-particles.
- Good technical feasibility of the coil system and sufficiently large space between coils and plasma for blanket and shield.

Although not specifically incorporated in the optimization procedure a reduction of anomalous transport caused by plasma turbulence is also expected in the Helias configuration. The geometrical structure of the magnetic field is a consequence of these criteria being simultaneously satisfied. In contrast to conventional approaches which start from a coil system and then calculate the magnetic field the method applied here is to optimize the magnetic field first and to compute the coil system afterwards using the Nescoil code .

The theoretical activities have been focussed on the issues of plasma equilibrium, MHD-stability and neoclassical transport. Furthermore, α-particle physics and plasma performance in a Helias reactor have been studied. Several numerical codes have been developed to support the optimization procedure; also a large effort has been devoted to the modular coil system and its technical feasibility. In the talk, an overview of these theoretical activities will be given.

MHD CONVECTION CELLS AND THE HARTMANN NUMBER

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Convection is usually a more effective heat transport mechanism than conduction. The boundary of the stable regime for zero-flow, axisymmetric, resistive MHD equilibria in a periodic cylinder seems to be characterized by a regime in which the resistive MHD equilibrium, rather than becoming turbulent, bifurcates into a helically-distorted equilibrium with a small but non-trivial amount of fluid flow. Originally demonstrated for a flat q(r) profile, the result has now been shown to be true for a rising q(r) previously considered by Waddell et al (1978, 1979), Carreras et al (1980), and Hicks et al (1981). Modifying the spectral-method incompressible MHD code of Shan et al (1991), we have considered random noise perturbations on three magnetically-identical initial conditions(1,2), all corresponding to the same q(r) profile. The only difference in the three runs is the numerical value of the kinematic viscosity employed. For the highest viscosity, the equilibrium is stable. For the intermediate value, the helical state with flow forms with only a single pair of (m,n) mode numbers and their harmonics in the saturated final state. For the lowest viscosity, a mixed final state with (m,n) = (2,1) and (3,2) and their harmonics is formed. It is important to note that conventional "tearing mode" theory, neglecting viscosity, gives identical predictions for all three cases. It is the Hartmann number H, rather than the Lundquist number S, that seems to govern the stability boundary. Accurate information on plasma viscosity comes to seem highly desirable in connection with MHD convection cells and their likely presence in tokamaks.

(1) X. Shan et al, Phys Rev. A44, 6800 (1991); D. Montgomery, Plasma Phys. & Contr. Fusion 34, 1157 (1992).
(2) X. Shan and D. Montgomery, "On the role of the Hartmann number in magnetohydrodynamic activity," Dartmouth preprint, 1992.

Fluid Simulations of ∇T_e-Driven Turbulence and Transport in Boundary Plasmas *

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This paper is a report on simulations of a new drift wave type instability driven by the electron temperature gradient in tokamak scrapeoff-layers (SOL).[1] A $2D(x,y)$ fluid code has been developed in order to explore the anomalous transport in the boundary plasmas. The simulation consists of a set of fluid equations (in the electrostatic limit) for the vorticity $\nabla_{\perp}^2\phi$, the electron density n_e and the temperature T_e in a shearless plasma slab confined by a uniform, straight magnetic field B_z with two divertor (or limiter) plates intercepting the magnetic field. The model has two regions separated by a magnetic separatrix: in the edge region inside the separatrix, the model is periodic along the magnetic field while in the SOL region outside the separatrix, the magnetic field is taken to be of finite length with model (logical sheath) boundary conditions at diverter (or limiter) plates. The simulation results show that the observed linear instability agrees well with theory, and that a saturated state of turbulence is reached. In saturated turbulence, clear evidence of the expected long-wavelength mode penetration into the edge is seen, an inverse cascade of wave energy (toward both long wavelengths and low frequencies) is observed. The simulation results also show that amplitudes of potential and the electron temperature fluctuations are somewhat above and the heat flux are somewhat below those of the simplest mixing-length estimates. The results from the self-consistent simulations to determine the microturbulent SOL electron temperature profile agree reasonably with the experimental measurements. The effects on the mode of neutral gas collisions at the divertor sheath and comparisons with the ionization driven turbulence will be discussed.

References

H. L. Berk, D. D. Ryutov and Yu. Tsidulko, Phys. of Fluids **3**, 1364 (1991); H. L. Berk, R. H. Cohen, D. D. Ryutov, Yu. Tsidulko, and X. Q. Xu, Nuclear Fusion (in press).

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* Performed by U. C. Berkeley for USDoE under Contr. DE-FG03-90ER54079 and by LLNL for USDoE under Contr. W-7405-ENG-48

Stabilization of the Tearing Mode by Overlap with Driven Alfvén Resonance Islands

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The stability of the tearing mode in the presence of driven Alfvén waves is studied numerically. The model is reduced resistive MHD in a sheared slab with a driving electric field to produce a resistive equilibrium with a peaked current density. The traveling Alfvén waves are driven at a frequency such that the Alfvén resonance is near the region of large current gradient. The temporal evolution is studied as a function of the driving frequency and amplitude. The results indicate that the tearing mode can be completely stabilized. Stabilization occurs when the Alfvén resonance islands overlap the current layer. Quasilinear flattening of the current profile, though plausible, does not appear to be the dominant stabilization mechanism. Rather, stabilization occurs because the Alfvén waves at large amplitude in a sheared magnetic field have shear flow in their direction of propagation. This shear causes the tearing modes to propagate and saturate at a lower level. At sufficiently large Alfvén wave amplitude, the tearing mode is damped. The role of self-consistent "magnetic field line" chaos will be discussed. These results suggest that it may be possible to stabilize tearing modes in a tokamak by exciting low frequency Alfvén waves of the same helicity.

Magnetic Islands and Their Effects in Tokamak Plasmas*

C. C. Hegna, J. D. Callen,
T. A. Gianakon, W. X. Qu, A. I. Smolyakov and J. P. Wang
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The vast majority of theoretical plasma physics investigations of tokamaks rely on the presence of a continuous symmetry in the magnetostatic equilibria so that the existence of a set of nested, toroidal magnetic flux surfaces is guaranteed. In this presentation we propose that the fundamental underlying magnetic topology of a tokamak plasma is not described by this idealized limit, but instead by a collection of magnetic island chains located at low-order rational surfaces and localized regions of intermittent magnetic stochasticity.

In particular, the fluctuating bootstrap current of neoclassical-MHD provides a robust mechanism for the formation of resonant symmetry-breaking magnetic perturbations and the resulting magnetic islands [1]. Simulations of interacting bootstrap-current-driven magnetic islands show that the distribution of magnetic island widths exhibit a quasi-equipartition where the steady-state magnetic topology is described by magnetic island chains radially separated by regions with toroidal magnetic surfaces that support plasma density and temperature gradients [2]. This result is in sharp contrast to the naive single-helicity theory (where island interactions are ignored), that would incorrectly predict that islands forming at low-order rational surface grow to be substantial fractions of the plasma confinement region and thus cause island overlap.

A self-consistent evolution of the plasma pressure profile in this magnetic topology is necessary to characterize the magnetic island dynamics and the subsequent plasma transport. A simple calculation of the quasi-static pressure profile near a single isolated magnetic island can be made [3]; however island interactions and time-dependent processes seriously complicates this calculation. Additionally, ideal ballooning mode stability can be significantly effected near a magnetic island when the ballooning mode is localized near the island X-point [4]. When many islands are present, the resultant steepening of the pressure gradient between islands can cause the equilibrium to approach the ballooning instability threshold. Hence, it is suggested that the process of enhanced ballooning mode instabilities induced by the magnetic island topology could contribute to anomalous plasma transport.

Additionally, the effects of finite ion banana orbits become important to the magnetic island dynamics when the island width is comparable to the ion banana width [5,6]. These effects may be particularly important to the high performance supershots of TFTR plasmas, where improvements in confinement and the appearance of MHD fluctuations are observed. In the context of the present model, we provide a plausible explanation for the phenomenology of the MHD modes observed in supershots [7].

* Research supported by U. S. DOE grant no. DE-FG02-86ER53218

[1] C. C. Hegna and J. D. Callen, Phys. Fluids B **4**, 1855 (1992).
[2] T. A. Gianakon, C. C. Hegna, and J. D. Callen, Bull. Am. Phys. Soc. **37**, 1595 (1992); 1993 Sherwood Theory Meeting.
[3] C. C. Hegna and J. D. Callen, Phys. Fluids B **4**, 4072 (1992).
[4] C. C. Hegna and J. D. Callen, Phys. Fluids B **4**, 3031 (1992).
[5] J. P. Wang, C. C. Hegna, and J. D. Callen, 1993 Sherwood Theory Meeting.
[6] J. D. Callen, A. I. Smolyakov, and C. C. Hegna, 1993 Sherwood Theory Meeting.
[7] Z. Chang, et al., 1993 Sherwood Theory Meeting.

Shear Damping of Toroidal Drift Waves*

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The conventional theory of high-n toroidal drift waves, based on the ballooning representation, indicates that shear-damping is generally reduced in a torus compared to its plane-slab value. It therefore describes the most unstable class of drift-waves in a torus. However, modes of this type can occur only if the diamagnetic frequency $\omega^*(r)$ has a maximum in r, and they affect only a small fraction, $0(1/n^{1/2})$, of the plasma radius around this maximum. Consequently they may produce little anomalous transport.

In the present work we show that, within the ballooning description, there is another class of toroidal drift-waves, with very different properties to the conventional ones. The new modes have greater shear-damping (closer to that in a plane-slab) than the conventional ones, and so have a higher instability threshold. However, they occur for any plasma profile and at all radii, and they have larger radial extent, comparable to the plasma radius. Consequently they may produce far greater anomalous transport than the relatively benign conventional modes.

This suggests a picture of anomalous transport in which the plasma profile is determined by marginal stability, but marginal to the new class of modes not to the conventional ones. This might explain why marginally stable profiles calculated for drift-waves with *plane-slab* damping sometimes agree well with the profiles in *toroidal* experiments. It is also consistent with the fact that experimental profiles may exceed instability thresholds calculated by the conventional application of the ballooning representation. The new modes may also be related to the long radial structures which appear in some plasma simulations and in experiments.

*Work supported by U.S. Department of Energy, UK Department of Trade and Industry, and Euratom.

HOW TO MAKE A HELIOTRON INTO A HELIAS LIKE A HELIAC FOR REACTOR STUDIES

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High performance computer codes are used to design advanced stellarators competitive with tokamaks for ITER. To this end a helical coil winding law has been found that is relatively simple and seems to have good spacing for a reactor. Most of the magnetic field comes from circular coils wound on an axially symmetric torus, but there is one large poloidal coil twisted to provide the harmonics necessary to achieve high β and ι. An argument can be made that advanced stellarators will operate largely in H mode. To understand this one must recognize the role of quasineutrality in determining a not entirely radial electrostatic field which has an important effect on transport.

Sherwood Theory Conference
March 28-31, 1993
Newport, R.I.

ASPAN: Advanced Spectral Analysis of TFTR Microwave Scattering

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We use the multiple taper theory of Thomson to estimate the local spectral density of turbulent fluctuations. A family of orthogonal tapers are used to produce many independent realizations of the underlying stochastic process. The tapers are optimally chosen to minimize the broad band bias. We analyze plasma fluctuations from two discharges of the TFTR microwave scattering diagnostic using ASPAN, a user friendly state-of-the-art signal processing code under development at New York University. The first discharge is enhanced fluctuations at the sawtooth crash in L-mode plasmas and the second is edge fluctuations during ELM activity in limiter H-mode plasmas. Both discharges have transient phenomena which are localized to relatively small time intervals and frequency bands. We compare the multitaper approach with more standard analysis method. We show that the periodogram is significantly biased when the spectral range is large. Furthermore, the adaptive multitaper significantly outperforms the smoothed periodogram for data lengths of 300-3,000 points i.e. the multitaper estimate converges more rapidly to the true spectrum as the datalength increases. In the Elm dataset, we find that precursors have a different spectral density than the ambient fluctuation spectrum.

*Princeton Plasma Physics Laboratory.
**AT&T Bell Laboratories.

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Kinetic Ballooning Stability of Experimental Parameters Including Shear Flow and Equilibrium Gradients*

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A fully gyrokinetic, fully implicit initial value code has been constructed in ballooning coordinates, with full kinetic treatments (including Lorantz collisions) of all plasma species. L-mode shots have been found to be within ± 20% of marginal stability inside the core (r/a < 0.5). However, a TFTR supershot pellet injection experiment by Zarnstorff et al. to test the marginal stability hypothesis is found to be 2-3 times past the critical temperature gradient threshold. Despite this, the gyro-Bohm normalized χ for this shot is comparable to or less than the similar L-mode shots which are within ± 20% of marginality. However, initial estimates indicate next-order equilibrium gradient effects may be important. We present an analysis which shows that these next-order effects can in general change ballooning instabilities to convective-like instabilities, which do not exponentiate indefinitely even in the linear stage. Initial perturbations will decay as $t \to \infty$ even though the equilibrium is well above marginality according to the lowest order ballooning theory. Quantitative evaluations of these effects for experimental parameters will be presented.

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

1993 Sherwood Theory Conference

Kinetic Effects on TAE and KTAE Modes*

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Thermal ion finite Larmor radius (FLR) effects on TAE and KTAE modes are studied base on a collisional electron and fully kinetic ion model. In the small Larmor radius limit ($b_\theta = (k_\theta \rho_i)^2/2 << 1$), the eigenmode equation reduces to the resistive MHD model previously employed to study the TAE mode and resistive periodic shear Alfvén eigenmode[1] due to finite toroidicity $\varepsilon = r/R$. Analytical as well as numerical results will be presented.

In the ideal MHD limit the TAE mode is localized in θ space within $\theta_t \approx O(\varepsilon^{-1})$, where θ is the generalized poloidal angle. The FLR effect is to allow the TAE mode to radiate its wave energy across and beyond the turning points θ_t, and thus the TAE damping rate is enhanced. In the limit $b_\theta s^2 \approx O(\varepsilon^3)$ the damping rate is similar to that calculated previously[2], where s is the magnetic shear. The presence of destabilizing fast ions can greatly nullify the enhanced radiation damping due to thermal ion FLR effect.

In the limit $b_\theta s^2 << \varepsilon$ the dispersion relation for the KTAE mode has an identical form as that for the resistive periodic shear Alfvén eigenmode[1] with $(i\nu/\Omega)$ replaced by $\tau = [i\nu/\Omega - (T_e/T_i+3/4)b_\theta]$, where ν is the plasma resistivity, and $\Omega = \omega / (V_A/2qR)$. Thus, KTAE is essentially the same branch of eigenmode as the periodic shear Alfvén eigenmode. The results indicated that due to FLR effect the lower KTAE branch, that accumulates at the lower continuum gap boundary, becomes more damped, and the upper KTAE branch, that accumulates at the upper continuum gap boundary, becomes less damped. For $(T_e/T_i+3/4)b_\theta >> \nu/\Omega$, the damping rate of the upper KTAE branch is very small and scales linearly with plasma resistivity ν. These features has been confirmed by the numerical solutions of the full kinetic equation.

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(Nearly) Portable PIC Code for Parallel Computers*

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As part of the Numerical Tokamak Project, we have developed a (nearly) portable, one dimensional version of the GCPIC algorithm[1] for particle-in-cell codes on parallel computers. This algorithm uses a spatial domain decomposition for the fields, and passes particles from one domain to another as the particles move spatially. With only minor changes, the code has been run in parallel on the Intel Delta, the Cray C-90, the IBM ES/9000 and a cluster of workstations. After a line by line translation into cmfortran, the code was also run on the CM-200. Impressive speeds have been achieved, both on the Intel Delta and the Cray C-90, around 30 nanoseconds per particle per time step. In addition, we were able to isolate the data management modules, so that the physics modules were not changed much from their sequential version, and the data management modules can be used as "black boxes".

*I would like to acknowledge use of the following computational facilities where these concepts and the GCPIC code have been tested and run: Office of Academic Computing (UCLA), National Energy Research Supercomputer Center (LLNL), Concurrent Supercomputing Facility (Caltech), and Advanced Computing Laboratory (LANL). This work was supported by Sandia National Laboratory and the U. S. Department of Energy.

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SHERWOOD THEORY MEETING 1993

Statistical and Transport Analysis using the MFE Database

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With the MDI Mathematica interface[1] and the recently defined generic naming convention[2], it is relatively easy to extract datasets from the MFE Database from any computer connected to the Internet. We illustrate the use of the MDI interface by extracting and computing a data file suitable for extensive statistical analysis. A Mathematica package that extracts the essential parameters and profiles from the database, computes the necessary gradients and other derived quantities, and formats and writes a datafile suitable for statistical analysis is presented. With minor modifications this same procedure can be used to construct input files for transport analysis codes.

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*Supported by USDOE Grant DE-FG05-88ER53266

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Far Field ICRF Sheath Formation on Walls and Limiters*

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A body of theoretical and experimental evidence suggests that unabsorbed wave energy in ICRF fast wave (FW) heating or current drive experiments can result in deleterious edge interactions. In this paper, a model describing the formation of far field sheaths due to FW interaction with material surfaces, is presented. Near conductors which do not conform to flux surfaces, an incoming FW causes generation of a slow wave (SW) component.[1] The $E_{||}$ of the SW is employed in the present model to drive an rf sheath, in a manner similar to what has been previously discussed for antenna (near field) sheaths.[2] To assess the importance of the proposed mechanism in past and future experiments, a heuristic scaling model of the resultant sheath voltage V has been developed and is used to compare V to the usual $3T_e$ Bohm sheaths. The model illustrates the important dependencies of V on the single pass absorption, edge density, rf frequency, FW cutoff location and limiter/wall geometries.

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Coherent Drift Wave Structures in Sheared Magnetic Fields*

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For the problem of calculating the coherent drift wave structures in sheared magnetic fields, we have found it useful to derive the governing nonlinear pde from a variational principle. The variational principle is based on the free energy functional $F[\varphi] = \int_V \mathcal{F}(\varphi, \nabla\varphi, x)dx\,dy$. The method is applied to the vortex with speed u derived in Su *et al.*[1], given by

$$\nabla^2\varphi = \left(1 - \frac{v_d}{u}\right)\varphi - \frac{S_m^2}{u^2}\left(x - \frac{\varphi}{u}\right)\left(x - \frac{\varphi}{2u}\right)\varphi \,.$$

where space is measured in units of ρ_s, $\varphi = (e\Phi/T_e)(L_n/\rho_s)$ and the magnetic shear parameter is S_m. While the linearized problem ($\varphi \ll ux$) describes the usual shear induced damping, nonlinear solutions with trapped flow ($\varphi > ur_0$) form nonlinear self-bound states, which are maxima of the free energy F. We discuss the analytic properties and the numerical procedures for solving these types of nonlinear pde's.

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Plasma Polarization and Tokamak Space Charge*

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Quasineutrality requires space charge, ρ_c, to be small,

$$\rho_c \sim en\lambda_D{}^2/r^2$$

where n is the electron density and λ_D the Debye length, but it need not, and typically does not, vanish. It is of course linked to radial variation of the electrostatic potential, and as such is expected to play a role in tokamak rotation and enhanced confinement. In a tokamak, the distinctive widths of ion and electron guiding center orbits produces charge imbalance in an easily understood manner. Unfortunately the explicit form of ρ_c, which is second order in the poloidal gyroradius and involves second radial derivatives of the equilibrium profiles, cannot be computed directly from known distribution functions: the second order distributions are not known and difficult to calculate. Considering the plasma as a dielectric medium, we note that space charge can always be computed from the divergence of the polarization vector (dipole moment per unit volume), **P**,

$$\rho_c = -\nabla\cdot \mathbf{P} \ ,$$

and that **P** is straightforwardly found from the *first order* distribution. Using known neoclassical results we determine the radial polarization and thus the flux-surface averaged space charge in the core region of a tokamak. The result provides a differential equation for the radial electric field, in terms of the ion density and temperature profiles. Modifications that would pertain in the edge region, which has special importance to enhanced confinement, are considered.

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CONFORMAL MAGNETOSONIC WAVES

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The propagation of linear magnetosonic waves in an arbitrary, current free, two-dimensional planar configuration with constant density ρ is solved explicitly with the help of a conformal transformation, without being restricted to a local approximation. The role of critical points, X- and O-points, is discussed. Explicit examples are presented, including the propagation of magnetosonic waves in a configuration with a magnetic island.

The relevant MHD wave equation for the perturbed vector potential a (in the absence of dissipation) is $\partial^2 a/\partial t^2 - (\nabla A_o)^2/(4\pi\rho)\, \Delta a = 0$. Since the background field is current-free, the unperturbed vector potential A_o is a harmonic function and the wave equation can be solved by introducing the conformal mapping $w = w(\varsigma)$ which changes the Laplace operator Δ_ς into $|w'(\varsigma)|^2\, \Delta_w$. Here a prime denotes complex differentiation. Choosing $w(\varsigma) = \int^\varsigma d\varsigma\, /A'(\varsigma)$, the wave equation takes the simple Cartesian form $\partial^2 a/\partial t^2 - \Delta_w a = 0$.

The pattern of the wave propagation can be identified in terms of a dual magnetic configuration which is obtained with a simple inversion. Magnetic energy is found to accumulate at $X-$ and $Y-$points and to be deflected by $O-$points with current lines. The application of a conformal transformation to more complicated configurations is straightforward and shows that the effect of the different singular points on the wave propagation combine at spatial scales of the order or larger than their distance.

Application of the Realizable Markovian Closure to a Two-Field Model of Dissipative Drift-Wave Turbulence*

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In studies of nonadiabatic drift-wave turbulence, it is generally acknowledged that a two-field model such as that of Hasegawa and Wakatani is needed in order to account for the nonlinear dynamics of both the ions and electrons. In the adiabatic limit, where $n \sim \phi$, these equations reduce to the scalar Hasegawa-Mima equation, which has previously been studied in the literature both by numerical simulation of the primitive dynamics and with statistical closure methods.

A general multiple-field statistical closure of the Markovian type, which incorporates *different* interaction time scales for the individual fields, has been recently proposed.[1] This multiple-field realizable Markovian closure (RMC) can be derived from the more sophisticated direct-interaction approximation (DIA) and shares with it two important properties: *realizability* and *covariance under arbitrary linear transformations*. Realizability guarantees that predicted energies are non-negative, while covariance ensures that these predictions are independent of the choice of variables used to formulate the closure equations.

In this work, the two-field realizable Markovian closure is used to study the Hasegawa-Wakatani equations for dissipative drift-wave turbulence. We compute the particle flux predicted by the RMC and compare it to the value obtained by conventional simulation methods. These results are contrasted with the quasilinear estimate, which has previously been shown to grossly overestimate the actual particle flux in the nonadiabatic regime.[2]

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Stability Of Toroidal Alfvén Eigenmodes Using An Initial Value Hybrid Code

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Abstract:

Toroidal Alfvén Eigenmodes (TAE) have been shown to exist, in a plasma, in the gap of the continuum spectrum. These discrete, global modes, induced by toroidicity, could be strongly destabilized by energetic particles as alpha particles produced in fusion reactions.

The TAE stability is determined by the competition of the driving term associated to the resonant interaction between the mode and the parallel motion of the energetic ions, and the coupling with the Alfvén continuum which introduces a damping.

An initial value code has been used to solve the reduced resistive magnetohydrodynamic (MHD) equations for the bulk plasma and the gyrokinetic equations for the high energy particles. The MHD equations have been expanded in the inverse aspect ratio $\varepsilon = a/R$ to the lowest order at which the toroidal corrections enter the equations (that is the third order in ε) and for low-β $[O(\varepsilon^2)]$. In the gyrokinetic part of the code the high energy particles are pushed using the electric potential and the parallel component of the vector potential as obtained by the MHD part of the code.

The linear dynamic of the Toroidal Alfvén Eigenmode in the absence of energetic particles has been studied, considering the resistive damping rate and the interaction with the Alfvén continuum. Results of non-linear simulations will be presented particularly referring to the MHD non-linearity. The MHD non-linearity is the result of the interaction of two Fourier components of the mode with poloidal and toroidal mode numbers respectively (m,n) and $(m+1,n)$ which oscillate in time at a frequency $\omega_0 \sim O(\omega_A)$ (ω_A is the Alfvén frequency). The coupling of the two modes leads to a perturbation of the poloidal flux function $\delta\psi$ with mode numbers $(m=1,n=0)$ slowly varying in time. Typically the non-linear effects are important when the $(m=1,n=0)$ component of the perturbations significantly modifies the toroidal $O(\varepsilon)$ corrections to the cylindrical equilibrium (hence the non-linear effects are expected to be important in the "gap region"). When this occurs, the structure of the Alfvén continuum is modified and the global mode interacts with the continuum leading to saturation.

The observed non-linear saturation of the Toroidal Alfvén Eigenmode will be compared with an analytical model based on a three mode coupling truncated scheme of the MHD equations. Moreover, a comparison of the relative importance between the non-linear MHD saturation and the saturation induced by the $E \times B$ trapping of the high energy particles will also be discussed.

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Self-Similar Transport

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We consider a particle chaotic motion through a stochastic web. Such a case is related to a passive particle motion in the convection problem, or to the field line diffusion of a forcefree magnetic field. It is shown that the origin of anomalous transport is the stickyness property of orbits near the boundary of islands. High accuracy sixth order simulation computations display various self-similar properties such as the areas of islands, the Lyapunov exponents in the islands' boundary vicinities, and other attributes. This information enables us to find the exponent μ of the anomalous transport $\langle |R| \rangle \sim t^{\mu}$, where R is a particle or a streamline displacement. Here $\mu < 1$ and μ can be obtained from first principles. Some probabilistic features of the anomalous transport are described, such as the distribution function of distances with its power-like spectrum, and the existence of non-ergodic orbits and their fractal properties.

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RESISTIVE BALLOONING MODES REVISITED

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The conventional theory for the resistive ballooning modes relies on a two space scale analysis, which is justified for weak magnetic shear. We have first, analytically and numerically, studied the RMHD (one fluid) model for resistive ballooning modes with average favorable curvature in the weak shear limit. It is found the average curvature has a strong stabilizing influence and also leads to a localization of the mode. Increasing magnetic shear leads to destabilisation of low mode numbers. High mode numbers are unaffected for $rq'/q \leq 1$. We have next studied the Reduced Braginskii Two- Fluid model of the resistive ballooning modes both numerically and analytically. We find that with the inclusion of the average curvature effects the two scale analysis for weak shear renders a new average equation which yields results which are significantly different from the conventional one fluid model. For $rq'/q = 1$, the low modes are more unstable ,while the high mode numbers are unaffected.

Global Wave Modeling of Electron Interactions with Fast Magnetosonic Waves*

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Electron interactions with fast magnetosonic waves are of interest for both direct electron heating and fast wave current drive (FWCD) in tokamaks. Here we apply the full wave ICRF code PICES[1] to examples of both of these applications. To account for a realistic description of the actual D-shaped magnetic geometry of present day tokamaks, PICES is interfaced with the 3-D MHD equilibrium code VMEC.[2] Likewise, to correctly model the real toroidal structure of both source and image currents in ICRF current drive antennas, PICES is interfaced with the 2-D recessed antenna impedance code RANT.[3] Both current drive and electron heating by fast waves can be strongly altered because of modification of the $k_{\|}$-spectrum by the poloidal magnetic field. A poloidal mode expansion in PICES allows such variations in $k_{\|}$ to be included correctly. Comparisons are made to observations of the direct electron heating profile on TFTR[4] and to the fast wave current drive efficiency on DIII-D.[5] PICES also makes definite predictions about results of future experiments on TPX, ITER, and Alfvén wave heating on TFTR.

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Nonlinear Damping of Drift Waves by Strong Flow Curvature*

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A single–equation model has been used to study the effect of a fixed poloidal flow (V_0) on turbulent drift waves. The electron dynamics come from a laminar kinetic equation in the dissipative trapped–electron regime. In the past, we have assumed that the mode frequency is close to the drift–wave frequency. Trapped–electron density fluctuations are then related to potential fluctuations by an "$i\delta$" term. Flow shear (V_0') and curvature (V_0'') both have a stabilizing effect on linear modes for this "$i\delta$" model. However, in the nonlinear regime, single–helicity effects inhibit the flow damping. Neither V_0' nor V_0'' produces a nonlinear damping effect.

The above assumption on the frequency can be relaxed by including the electron time–response in the linear part of the evolution. In this time–dependent model, instability drive due to trapped electrons is reduced when mode frequency is greater than drift–wave frequency. Since V_0'' produces such a frequency shift, its linear effect is enhance. There is also nonlinear damping, since single–helicity effects do not eliminate the shift.

Renormalized theory for this model predicts nonlinear stability for sufficiently large curvature. Single–helicity calculations have already shown nonlinear damping, and this strong V_0'' regime is being explored. In the theory, the Gaussian shape of the nonlinear diffusivity is expanded to obtain a quadratic potential. The implications of this assumption will be tested by solving the full renormalized equation using a shooting method.

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2D NONLINEAR DYNAMICS OF FOUR DRIVEN VORTICES

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The interaction of four, driven alternately counter-rotating vortices in a two dimensional box, with impenetrable free-slip boundary conditions in the x direction and periodic conditions in the y direction, has been studied numerically. For viscosity $\mu \geq \mu_1$ the nonlinear state consists of four, alternately counter-rotating vortices. For a lower viscosity the system evolves to a state consisting of four vortices and shear flow generated by the "peeling" instability. For a still lower value of the viscosity the system undergoes a Hopf bifurcation. This time periodic state is caused by a secondary instability associated with vortex pairing. For a further decrease in the viscosity a global bifurcation gives rise to a periodic state during which the vorticity of the shear flow reverses. At even lower viscosity, there is a transition to a steady state, involving dominantly shear flow and a two-vortex state. Finally a complex bifurcation scenario to a temporally chaotic state follows for a further reduction in the viscosity. These results will be compared to some recent experiments in fluids with driven vortices.

Hamiltonian Attractors and Iso-Topological Relaxation in Reduced Magnetohydrodynamics*

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It is well known that a finite-dimensional dynamical system has regular or chaotic attractors only if the system is dissipative. Regular attractors are also possible in *infinite-dimensional Hamiltonian systems* in the sense that an initial state will relax to an attractor, the excess of the phase volume and the energy being hidden in an "invisible" small-scale, small-amplitude turbulence. This type of evolution has been known for a decade for non-integrable modifications of the KdV and the nonlinear Schrödinger equations possessing a finite number of the integrals of motion, where the attractors are stable solitons of universal shape.

New features of Hamiltonian attractors are revealed for hydrodynamic-type systems, such as two-dimensional (reduced) magnetohydrodynamics, where, due to topological constraints, the number of the integrals of motion is infinite. In this case the attractors are stable vortices of a non-universal (that is, depending on the initial conditions) shape, which, however, can exhibit universal kinds of singularities — current sheets terminating at triple points. We arrive at this conclusion using a heuristic approach based on the analysis of the canonical (Gibbs) distribution of the system's eigenmodes and the resolution of the arising ultraviolate catastrophe. The singular structures predicted by the theory appear to be observed numerically [D. Biskamp and H. Welter, "Dynamics of decaying two-dimensional magnetohydrodynamic turbulence," Phys. Fluids **B1**, 1964 (1989)].

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Theoretical Analysis of the Emissions at the Cyclotron Frequency Harmonics of Fusion Produced Alpha Particles*

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We are developing an extensive theoretical model to explain radiation emission at the harmonics of the alpha particle cyclotron frequency observed from D-T plasmas in JET [1]. We incorporate into our linear analysis [2] the corrections due to the curvature drift frequency and elucidate their dependence on mode number in order to identify the range of the most unstable wavelengths. We also explore in greater detail the role of impurites [3] and find that they may be responsible for some of the smaller peaks observed in the low frequency ($\omega < \Omega_\alpha$) portion of the emission spectrum. Finally we give our argument for the non-linear effects of the considered mode [4]. Our considerations are consistent with the experimental results [1] which show a strong correlation between the radiation power emitted and the neutron rate.

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Local Shear in General Magnetic Stellarator Geometry

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There has been relatively little work on microturbulence in stellarators. Bhattacharjee *et al.* [1] gave a purely numerical illustration of linear instability for the simplest cold ion electrostatic drift wave using a general magnetic geometry ballooning mode representation. This approach was recently extended by N. Dominguez *et al.* [2] with emphasis on analytic formulas derived from a single stellarator harmonic and a treatment of dissipative helical well trapped electron modes. Neither paper treats the puzzling question: How are high-m modes radially localized in stellarators with weak or no global shear? Since diffusion is likely proportional to the square of radial mode widths, this is as important as determining the growth rate. This paper argues that modes are localized by local shear not global shear. Local shear arises from the fact that the helical ripple from the external coils providing the stellarator transform increase with radius. Following Ref. 2, we note that local curvature from the helical ripple can localize the modes along the field lines. Thus we argue that stellarators with no global shear and favorable average curvature (W7-AS) should have the same basic transport as torsatrons (Heliotron and ATF) with global shear and average unfavorable curvature. In detail we derive a complete along the field line nonlinear ballooning mode formalism in magnetic coordinates for general stellarator geometry. We apply this to the case of a single helical harmonic. For illustration, we derive a formula for diffusion from collisionless helically trapped electrons modes proportional to the square of the local shear. The model diffusion matches the universal gyroBohm LHD stellarator scaling.

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*College of William and Mary, Williamsburg, Virginia.

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INVESTIGATION OF THE EFFECT OF EXTERNAL MAGNETIC PERTURBATIONS UPON DIVERTOR HEAT LOAD

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The heat load on a divertor target plate is spread over a wider region as the magnitude of the radial thermal conductivity in the edge plasma is increased. This observation gives rise to speculation that "ergodization" of the edge plasma, through deliberate external magnetic field perturbations, could be employed to reduce the peak heat load on the divertor target plate in TPX or ITER. As ergodization does not apply in the region of open field lines, this concept merits a sceptical view and careful numerical study.

We have developed computer programs to model the effect of non-axisymmetric magnetic perturbations upon divertor heat load, and have explored what kind of externally applied perturbations are the most effective for heat load reduction without destroying core plasma confinement. Our work relies on a grid-free random-walk method to solve a highly anisotropic model heat transport equation in a realistic perturbed tokamak magnetic field. The walkers are launched in the core plasma and make small steps across the magnetic field and long steps along the field lines; the latter steps are evaluated by accurate field line integration. The distribution of points where the walkers cross the boundary is interpreted as the heat load on the boundary. This is a model equation, because we do not consider the dependence of parallel conductivity on temperature, nor do we solve for a consistent density profile. Only the (constant) ratio of parallel to perpendicular diffusivity is important. The efficiency of this random walk calculation is greatly improved by use of splitting and Russian roulette.

We find that a carefully optimized set of coils located about 0.1 m outside the separatrix in TPX (or about 0.3 m outside the separatrix in ITER) can be used to spread the heat load over about 0.03 m in TPX (0.1 m in ITER) perpendicular to flux surfaces at the divertor plate, even at a very low level of anomalous cross-field heat transport. Such a spreading would significantly extend the permissible regime of operation for these devices. However, a similar beneficial effect is impossible to obtain if, for engineering reasons, the perturbing coils must be positioned significantly further away from the main plasma.

ABSTRACT

1993 International Sherwood Fusion Theory Conference
FEEDBACK CONTROL OF TOKAMAK INSTABILITIES

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We have made extensions and adaptation of theories of modern control science for lumped parameter systems (ODE) to distributed parameter systems (PDE), like plasmas [1, 2]. Experimentally, we have performed several successful experiments in feedback stabilization of $\vec{E} \times \vec{B}$ rotationally driven mode and an ITG instability [3]. We now propose generalization of the feedback theories so that they are applicable to multimode instabilities in tokamaks. We also propose unique suppressor structures suitable for tokamak applications. Specifically, we propose a modulated neutral beam suppressor for the control of major disruptions via feedback suppression of tearing [4] and/or kink modes. The suppressor action is modelled by the beam momentum, particle and energy input in the respective conservation equations. We also propose a scheme for the control of the thermonuclear thermal instability via feedback modulated biasing of a poloidal divertor suppressor. The modulated biasing will result in an electric current and an associated heat flux along the magnetic field in the scrape-off layer. With an appropriate phase and amplitude this in turn will enhance the radial power loss to reduce the core temperature excursion and stabilize the instability. The necessary feedback power levels for ITER-like parameters will be estimated in both cases.

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Alpha Heating Predictions for DT Supershots*

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In this paper we discuss ways to measure alpha heating in DT supershots in TFTR. The most direct way will be to compare the electron temperature profiles in a sequence of supershots where the mix of neutral-beam-injected D and T is varied from discharge to discharge. Ideally this would be varied from all D, to half D - half T, and then to all T to facilitate the separation of the isotopic and beam penetration effects from the alpha heating of the electrons. This alpha heating is expected to increase T_e steadily during the neutral beam injection (NBI) phase, to lengthen the duration of the T_e flare-up that is normally seen after turning off the NBI, and to increase the rate of reheat after the post-NBI sawteeth. The heating could also be seen by increasing the density in the post-NBI plasma (for instance by injecting a pellet) to rapidly slow down the alpha particles. The best supershots for such a sequence would have a long duration (> 0.5 sec) of relatively constant neutron emission (without disruptions, impurity blooms, or large MHD events).

An experiment was conducted in TFTR to explore the ranges of NBI power and $\beta_{norm} \equiv 10^8 \langle\beta\rangle a B_0 / I_p$ for supershots with sustained, relatively constant high neutron emission rates, and to optimize them in preparation for DT experiments during the coming year. Such sustained supershots can be reproduced with a major radius of $R_0 = 2.45$ m, injected NBI power up to 25 MW, and β_{norm} up to 2.0. They had fishbone-like activity. Discharges with very similar parameters up to the time of peak neutron emission did not sustain the peak rate, exhibiting a 10 - 30 % decrease in the neutron emission and confinement within the following 0.4 sec. They had coherent MHD activity with (m,n) = (3,2) or (4,3). MHD-quiescent supershots could be reproduced only with large R_0 (> 2.5 m). They did not have sustained peak neutron emission rates.

We analyzed these DD discharges in detail, and used them as a basis to model the expected alpha parameters in their DT analogs. The TRANSP plasma analysis code was used to give detailed predictions of the fast alpha distributions, slowing down, and heating[1]. The fusion yield is expected to be 6 MW and the alpha heating of electrons to be 1 MW. We modeled the increase in T_e using different assumptions about the isotopic dependence of the energy transport. If the transport is independent of the D -> T substitution, the central T_e is predicted to increase approximately 1 keV in MHD-free DT supershots with sustained high neutron emission. If coherent MHD activity occurs, alpha parameters such as the alpha heating and density are predicted to decrease.

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Instantaneous Phase-Space Lyapunov Expansion Rates in Coulombic Many-body Systems*

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In dense plasma systems the higher order correlations are important, particularly for quantities such as entropy flows. They are, however, costly to calculate. We consider the Lyapunov exponents in 6N-dimensional phase space (as opposed to the one-body exponents explored in many plasma physics applications). We conjecture that the instantaneous Lyapunov expansion rates in phase space contain information about entropy production and correlation evolution because of their connection to phase mixing and the loss of information about initial states.

Lyapunov exponents are commonly calculated by evolving two trajectories whose initial phase points are separated by a small randomly chosen phase vector. The phase separation may be rescaled continuously to the magnitude of the initial separation, in which case the Lyapunov exponent is simply the long-time average of the scaling factor.

The scaling factor is the Instantaneous Expansion Rate. Plots of its evolution typically show an initial rise followed by a decline towards an apparently asymptotic level characteristic of the system. This transient behavior tends to overwhelm and mask effects due to the underlying system evolution.

A method is developed to place the initial separation direction beyond the transient peak, close to the "asymptotic" region. An examination of fluctuations in the "asymptotic" expansion rate reveals correlations with the global dynamics. We give an example for a dense plasma (Gamma > 1) using a screened coulomb potential for which higher order correlations may be expected to be important. We show its behavior when quenched from a liquid temperature to below its freezing point.

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Gyrokinetic iδ Particle Model of Dissipative Trapped Electron Mode Turbulence*

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Dissipative trapped electron modes (DTEM) are considered to be one of the primary causes of the fluctuations at the core of tokamaks. We are pursuing two complimentary computational approaches to study DTEM turbulence. One involves a gyrofluid description for the ions and the other, to be reported here, a gyrokinetic particle representation.

Our gyrokinetic iδ model of DTEM consists of particle ions which follow the characteristics of the gyrokinetic equation. The electron physics is determined by the Boltzmann relation between density and potential fluctuations. Electrons trapped in the magnetic ripple along a field line contribute a small phase shift iδ between density and potential that drives wave growth. The use of a simplified electron description allows us to concentrate on the ion dynamics. The model has been implemented in two-and-one-half-dimensional sheared slab geometry. The velocities and positions of the particle ions are advanced in time according to gyro-averaged equations of motion using a predictor-corrector scheme. Passing and trapped electrons are treated analytically and their contribution appears in the gyro-averaged Poisson's equation as $\tilde{n}_e/n_{e0} = |e|\,\phi/T_{e0}\,(1-i\delta)$. The resulting nonlinear Poisson's equation is solved iteratively by a renormalization technique which insures efficient convergence.

The linear and nonlinear properties of the gyrokinetic iδ model are currently being compared to those obtained with a full dynamics implementation for the particle ions. The linear growth rates obtained from the particle models and solutions of the relevant eigenmode equations by shooting techniques are also being compared. Results from these ongoing studies will be presented.

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Transport Simulation of Advanced Tokamak Operations

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Plasma confinement and performance for advanced tokamaks are likely to be limited by magnetohydrodynamic stability. Transport simulation studies are carried out to evaluate the effectiveness of current profile control in raising the stability limits thereby allowing for high confinement and high beta operations in steady-state. We focus on advanced tokamak regimes with experimentally-demonstrated confinement improvements in the plasma core, such as high plasma internal inductance ℓ_i, and negative central magnetic shear. Key issues to be addresses include the relationship between current profile and pressure profile, coupled through the bootstrap current, in order to improve plasma stability, and the optimum ratio of bootstrap current and rf-driven current to minimize rf power requirement and maximize performance.

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3D MHD Simulations of Helicity Injection for Fluctuation Suppression in RFPs*

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DC electrostatic helicity injection for RFP configurations is simulated by computations of the resistive MHD equations to investigate fluctuation suppression. Earlier results show that mean fields can be modified to achieve configurations that are stable to tearing modes resonant inside the reversal surface.[1] This creates unbroken flux surfaces in the core, where standard RFP configurations are turbulent. Recent analysis of the power flow in the system has led to guidelines for the design of an experimental system. The resonant modes lose power to the mean current at large radii. To effect fluctuation suppression, the injected power must be delivered to the mean current in the region where the resonant modes lose power. The direction of the electric field induced by the electrodes determines how far the power from the injection system penetrates. The spectral content of the induced field determines the possibility of undesireable nonlinear coupling. If the induced field contains modes that can couple with two unstable resonant modes, the injected power will drive the modes directly. Therefore, configurations that induce m=0, low |n| perturbations are not acceptable. Also, low impedance circuits are not practical. A configuration of segmented, axial electrode strips--that induces predominantly axially symmetric, azimuthal electric field--has demonstrated the best combination of characteristics.

An RF current drive system has also been proposed.[2] Initial modeling efforts simulate the current drive with an ad hoc force on the electron fluid, directed parallel to the mean magnetic field. This has produced preliminary information about how sensitive the stabilization is to variations in the RF-driven current profile.

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Multi-species, two-velocity, one-space Fokker-Planck Code

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Discussion of a new Fokker-Planck code is presented. The code performs a kinetic simulation in two velocity coordinates and one space coordinate (aligned along the magnetic field) of a multi-species plasma using a Rosenbluth potential formulation to handle the collision term, and is being used to examine various plasma conditions where the standard fluid approximations are invalid. Some results comparing the collisionless and collisional sheath are presented.

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Coupling Transport Fluid Codes in 1D and 2D

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ABSTRACT

The modeling of diffusive transport between the core and the edge of a magnetically confined fusion plasma by means of independent codes that operate on different space and time scales is addressed.

Two 1D codes are run simultaneously, one representing the edge and one representing the core. The "edge code" is typically run with a finer space resolution than the "core-code", because of the short spatial scale introduced by rapid parallel loss to the divertor or limiter in the scrape-off layer (modelled here by a simple loss term). The "code merging" approach [1-3], already developed for electrostatic particle simulation is here extended to the solution of the diffusion equation, providing a full self-consistent simulation while preserving a substantial degree of independence of the codes. Different models have been tested for the density and heat transport equation.

The original "code merging" scheme is also applied to couple non-linear models solved via the Newton iteration method. In particular it is shown (analytically and numerically) that if the self-consistent solution scheme is applied at each iteration stage, then the exact solution, *i.e.* that which would have been found by solving the whole system in a single code, is obtained.

Simulation examples are shown and compared with the most straighforward iterative approach for code coupling, where the self-consistency is obtained by iterating the separate solutions to achieve continuity of the field variable and its derivative at the interface.

A model is also presented in which a 2D transport code for the edge is coupled to a simple 1D transport code for the core plasma. In this case the 1D code provides, in a self-consistent fashion, essentially a time-varying boundary condition for the average density, temperatures, etc. on the inner boundary (core-edge interface) of the 2D domain. Results are shown for a simple model which follows a single field variable (density or temperature).

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NONFULLY DEVELOPED SATURATED STATES IN THE MICROTEARING MODEL FOR MAGNETIC EDGE TURBULENCE*

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Strong plasma turbulence, in particular, turbulence in which saturation is achieved through spectral transfer by mode coupling, is generally regarded as being fully developed, i.e., as having a saturated final state that is independent of initial conditions. For fully developed turbulence, the robust features of the turbulent state, such as the fluctuation level, spectrum, and the transport coefficients, depend only on parameters specifying the equilibrium, not on the initial configuration of fluctuation energy. For turbulence which is not fully developed, the properties of saturated states resulting from identical equilibrium conditions must be described through an ensemble average[1], and any given realization of the saturated state can be quite different from the ensemble average state. Under such a situation, perturbations applied to the turbulence might induce a transition to a different member of the ensemble, producing a turbulent state with different properties.

Microtearing turbulence, a model that has been invoked in the context of magnetic fluctuations in the tokamak edge[2], represents a system in which saturated turbulence is not fully developed. In this presentation, the results of numerical solution of the microtearing model equations are presented, and detailed analysis is given in order to identify the physical processes that underlie the evolution toward differing final states for identical equilibrium parameter configurations. A number of other unusual features of the turbulence are examined, including saturated states in which the magnetic and internal energies are grossly non-equipartitioned even in the small scales; pumping of the internal energy by the magnetic energy away from a condition of unstable equipartition to the non-equipartitioned state; and non-stationary saturated states with nearly periodic bursting of the total energy. The dynamical processes associated with these phenomena are discussed in terms of properties of the basic and renormalized equations.

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Estimating Tokamak Plasma Transport Scaling via Gyrokinetic Particle Simulation*

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Three Dimensional Electrostatic Gyrokinetic particle simulations of ion temperature gradient driven (η_i) instabilities have been carried out using parameters consistent with tokamak plasmas (e.g. L-mode type discharges. etc.) to study scaling of the heat flux. The scaling for the heat flux is found to be gyro-Bohm. We start with a simple ion-electron plasma assuming an "adiabatic" response and no self-generated shear flow. In the linear stage of the simulation the poloidal wavenumber spectrum peaks near $k_y \rho_s \sim 0.5$. In the nonlinear stage there is an energy cascade to longer poloidal wavelength modes ($k_y \rho_s \sim 0.2$). This peak at the longer poloidal wavenumbers is more consistent with experimental observations of the poloidal wavenumber spectrum. Along with this energy cascade a change in the radial mode structure is observed. Self-generated shear flow is then included first using an "adiabatic" response for the electrons, and then a "nonadiabatic" response. This self-generated shear flow is found to reduce the level of the steady-state flux for the case of "adiabatic" electrons, while the effect appears to be less pronounced when a "nonadiabatic" response is used for the electrons. The inclusion of self-generated shear flow also changes the character of the energy cascade previously discussed.

Finally, the effects of impurity ions are considered. Impurities are found to reduce the saturation level of the potential fluctuations (and the corresponding heat flux) depending on the concentration of the impurity species. Impurity heat and particle transport scaling will also be presented for several impurity ion species.

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CURRENT DRIVEN BALLOONING MODES IN HIGH-q_0, HIGH-β_p TOKAMAKS*

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Investigation of low-n external modes in high-q_0, high-β_p tokamak equilibria with finite to large magnetic shear throughout, and lying in the second stability region for $n = \infty$ ballooning modes reveals a potential instability of rather unique characteristics. It has large poloidal m numbers, is driven by the current density gradient and is localized near the plasma edge on the large-R side of the torus. Such a mode is stable for sufficiently large nq, consistent with being in the $n = \infty$ second stability region. However it is unstable for intermediate values of nq, above a beta threshold that scales as $\beta aB/I = C$, the numerical value of C being surprisingly low. To a good approximation an invariance with regards the scaling $\beta_p \rightarrow \beta_p$, $q \rightarrow \lambda q$, $n \rightarrow n/\lambda$ is manifest. The mode radial structure is characteristically "ballooning" with fast radial oscillations associated with the rational surface spacing, and a longer scale envelope that encompasses many m-components. This allows an analytic treatment along the lines of finite $1/nq$ ballooning theory. The numerical study of these modes with conventional MHD codes is difficult due to the occurrence of many closely spaced rational surfaces near the plasma edge, and a plethora of numerical convergence problems has being encountered. These modes may be important in order to explain ELM's and beta collapses in low current, high-β_p discharges. It is shown that their stability can be improved with a reversed edge current density.

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Nonlinear Studies of Vortex Dynamics in Non-neutral Plasmas*

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Magnetized electron plasmas in cylindrical geometry are known to exhibit long-lived coherent structures associated with stable or unstable diocotron modes[1]. Using low-noise particle simulation techniques that integrate the full-dynamics or the guiding center equations of motion, we study linear and nonlinear evolution of diocotron modes in a cylinder with periodically identified ends. Hollow density profiles, ranging from a delta-function distribution to a more gentle but still nonmonotonic profile, tend to spontaneously exhibit an $l = 3$ mode. The nonlinear evolution of this mode fills the center, leading to a monotonic density profile. Starting with a monotonic profile and exciting a mode with $l < 3$, we have observed long-lived vortices that tend to survive indefinitely. Comparisons with known experimental and theoretical results will be presented.

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Diffraction Corrections to Ray Propagation in a Magnetized Plasma*

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The geometric optics approximation is the commonly used description for wave propagation in media where the usual local WKB conditions are satisfied. However, diffraction phenomena can give important corrections to a ray trajectory and scattering description when focussed waves are launched. The general mathematical description for such electromagnetic beams is formulated for a magnetized plasma and solved analytically for a cold plasma with spatial inhomogeneity in only one dimension. This analytic solution is detailed for X and O mode gyrotron propagation in modeled tokamak plasmas. Three-dimensional numerical solutions are discussed.

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Dual Cascade and Minimum Enstrophy State in the Tokamak Scrape-Off Layer

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In the Tokamak Scrape-off layer (SOL), there is experimental,[1] theoretical,[2] and computational[3] evidence of an inverse energy cascade, wherein fluctuation energy transfers nonlinearly to large scale lengths. If the inverse cascade proceeds to the largest scales, it gives transport which is inherently nonlocal, precluding standard descriptions with local transport coefficients. This includes DIA based renormalization theories, γ/k^2 "mixing length" theories, and spectral or pseudo-spectral codes, all of which tend to involve a two-scale assumption, that turbulence acts on very short time and length scales relative to the equlibrium. The two-scale assumption is violated by turbulence undergoing a significant inverse cascade, and a different approach is called for.

We postulate that the net effect of such turbulence is not local transport, but rather to supply the equilibrium with a steady source of energy at the minimum enstrophy. The form of the supplied energy is assessed through a variational calculation, which gives an equation for the equilibrium velocity profile, $\nabla^2 \mathbf{V} = \lambda^2 \mathbf{V}$, where λ^2 is an undetermined Lagrange multiplier. For a slab model, the solution in the SOL is $V = V_a \exp\left[-\lambda(r-a)\right]\hat{y}$, where V_a is the poloidal velocity at the SOL/edge interface. This velocity (from $E \times B$ in our simple model), leads to the potential profile, $\phi = -((V_a B/\lambda c)\exp\left[-\lambda(r-a)\right]$. For field lines connected to an endplate $e\phi = \Lambda T_e$, (where $\Lambda \sim 4$ is nearly constant) giving also the T_e profile. Thus, the profiles are given and the transport problem is solved, up to the two unknown constants λ and V_a. One relation comes from heat balance. There are several candidates for the second constant, and we will present numerical simulations which evaluate these.

In addition to numerical analysis of our closure scheme, we will present extensions of the solution to more realistic divertor geometries, and experimental comparisons.

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Exploration of Stellarator Orbit Topology Using J^{**}

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Stellarator orbits are best displayed in Boozer coordinates[1] because the helical twist of the system is removed and because the slow drifts are naturally separated from the faster bounce motion. Even more insight into the orbits is gained using the concept of J^{**}[2]. J^{**} is the average of P_ϕ (the toroidal canonical momentum) over one field period. In contrast to the integral for J (the usual third adiabatic invariant), the J^{**} average (in Boozer coordinates) is taken over toroidal angle at fixed flux surface (ψ) and poloidal angle (θ). In a single field period, all orbits are either circulating or are trapped (helically) within the field period. The contours of constant J^{**} represent a good approximation to the guiding center orbits. Note that the value of J^{**} may jump across the trapping boundary.

Various aspects of the orbit topology are determined by the magnetic field topology along the same ψ = const., θ = const. paths. The $B_{\rm min}$ contours coincide with the orbits of the most-deeply trapped orbits. The $B_{\rm max}$ contours correspond to the trapping boundary. Thus, these features are independent of the energy, mass, and charge of the particle. In contrast to tokamaks, if stellarators contain trapped particles at low energy, they also do so at high energy.

Stellarator design efforts have tried to maximize the area of closed $B_{\rm min}$ contours as an indication of improved orbit confinement. However, this view is too narrow, and the confinement of transitional and circulating orbits may be at least as important.

J^{**} is easily calculated on a PC using the Fourier harmonics of $|B|$ in Boozer coordinates. For a given configuration, and for a given energy, the entire orbit topology may be displayed for each value of E/μ (μ = the magnetic moment) which corresponds to a $B_{\rm max}$ contour. This approach has identified numerous pathologies in the orbit topology. Bananas may occur on the outside and inside of the machine. The "barely-trapped" orbit becomes trapped off the midplane. All bananas eventually become helically-trapped orbits.

The situation becomes more complicated when an electric field is introduced. We will assume that the potential is constant on a flux surface. If this is not the case, there may be large convective losses in the plasma due to radial $\boldsymbol{E} \times \boldsymbol{B}$ drifts. The J^{**} orbit topology must now be examined for each assumed potential profile. Several new effects appear. Particles may be contained (or ejected) by the potential electrostatically. The poloidal $\boldsymbol{E} \times \boldsymbol{B}$ drift winds or unwinds the helically-trapped orbits. In ATF, for example, the region of confined helically-trapped ions moves from the inside of the plasma to the outside of the plasma when an electric field is added.

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Plasma Potentials Generated by Microwaves Incident on a Magnetic Gradient: Theory and Computer Simulation*

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It is well known that steady-state potentials can be generated within a plasma by microwave heating, as, for example in the Tandem Mirror with thermal barriers,[1] where the generated potentials are negative in sign and result from distortions in the hot-ion population and in the electron velocity distribution caused by microwave heating. There are other situations, however, where the creation of transient, positive-going, potentials is desirable. An example is the Mirrortron[2] ion accelerator, where a traveling positive potential wave accelerates ions to high energies. Another example is the use of time-correlated transient potentials to enhance confinement in multiple-mirror systems.[3] This paper examines theoretically and computationally the generation of localized, transient, positive space charge potentials by pulsed microwaves incident on a plasma on a magnetic gradient. In this situation, the sudden increase in perpendicular electron energy caused by the microwaves results in an increased $\mu\nabla B$ force on the electrons, hence to their partial expulsion down the magnetic gradient, resulting in a localized positive-going potential. A theoretical estimate of the magnitude and spatial distribution of this potential is derived from combining quasineutrality with the $\mu\nabla B$ effects associated with a microwave-perturbed electron velocity-space distribution. A computer simulation of the process is obtained by using the GYMNOS particle-in-cell code.[4] The advantage of the code calculation over the analytical result is that the code permits an evaluation of the time-dependent nature of the potentials, whereas the analytical result is, in effect, only a quasi-steady-state representation.

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A Toroidal Gyrokinetic Poisson Solver*

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A numerical scheme for solving the gyrokinetic Poisson equation in toroidal geometry using the Bessel function expansion techniques has been developed. Because of the poloidal and toroidal variations are decoupled in the gyrokinetic Poisson equation for a poloidally symmetric background, the same equation is valid for both cylinderical and toroidal geometries. Both the WKB method and the Galerkin method have been used to capture the slow radial variation of the background inhomogeneity. The results have indicated that the WKB scheme is adequate to account for the typical denisty and temperature variations in the tokamak experiments. On the 8k CM200 machine, our Poisson solver uses 0.32 CPU seconds for a $64 \times 64 \times 64$ grid mesh. It compares well with the time of 0.1sec for using the FFT on a Cartesian grid of the same mesh size. Solutions of $\nabla_\perp^2$ approximation of small gyroradius limit is also examined.

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Charged-Particle Stopping Powers in Inertial Confinement Fusion Plasmas

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Abstract

A new, generalized Fokker-Planck equation that properly treats large-angle as well as small-angle binary collisions has been used, together with an analysis of electron quantum degeneracy and a consideration of the important effects of ion stopping, to calculate the stopping power for 3.5 MeV α's in D-T pellets . Since this approach is valid even when the Coulomb logarithm $ln\Lambda_b \sim 1$, it is useful in the study of inertial confinement fusion plasmas (ICF) and other plasmas in which $ln\Lambda_b \gtrsim 1$ (i.e. both moderately and weakly coupled plasmas). At full ICF pellet compression, when the plasma fuel is cold ($T_e \lesssim 1$ keV and $ln\Lambda_b^{\alpha/e} \sim 1$), inclusion of quantum degeneracy effects results in a factor 3 increase in the stopping power. In the period from ignition ($T_e \sim 10$ keV) to peak burn ($T_e \sim 20$ - 40 keV) when $ln\Lambda_b^{\alpha/e} \simeq$ 4-6 and $ln\Lambda_b^{\alpha/i} \simeq$ 10-12 and quantum degeneracy is unimportant, ion stopping contributes significantly. At $T_i \sim 20$ keV, for example, about 46% of the α energy is transferred directly to deuterons and tritons rather than electrons. Consequently the α range (R) and ρR are reduced by about 60% from the case of pure electron stopping.

NONLINEAR TWO FLUID THEORY OF PROPAGATING MAGNETIC STRUCTURES

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In high temperature plasmas, magnetic perturbations that are related with field reconnection propagate with a finite frequency due to diamagnetism. We derive a set of non-linear equations that describe single-helicity perturbations, using a two-fluid theory. We prove that the electron equations, which include finite electron mass, can be integrated once irrespectively of the ion response. These equations show that, in general, the current density is not constant on magnetic surfaces and that large current densities tend to develop at the magnetic separatrices. Electron inertia limits the magnitude of these currents.

The governing equation for the magnetic flux is derived in the limit where the ion gyroradius ρ_i is either large or small as compared to the radial width of the perturbations. In these two limits the ion response has a simple functional dependence on the electrostatic potential.

The large ρ_i limit is appropriate for the discussion of the current singularities and of the effects of electron inertia. In this limit the governing equation reads

$$\tilde{J} = A(u, u_*) \left[1 - \frac{x}{\sqrt{G(\psi, \tilde{J})}} \right], \quad (1)$$

where $\psi = \psi_o(x) + \tilde{\psi}(x,\ y - ut)$ and $\tilde{J} = \nabla^2 \tilde{\psi}$. The constant A depends on the propagation velocity u and on the diamagnetic velocity u_*. The function G depends linearly on the flux function ψ and nonlinearly on the current density $\tilde{J}$. This latter dependance vanishes in the zero mass limit.

A number of properties that characterise the spatial stucture of the solutions of Eq.(1) near the singularities are discussed in different frequency intervals and the relationship between linear and non-linear solutions is clarified.

LOW-FREQUENCY SHORT-WAVE-LENGTH ELECTROMAGNETIC FLUCTUATIONS IN A PLASMA AND ANOMALOUS HEAT CONDUCTIVITY

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Within the General Renormalized Statistical Approach, the stationary spectra of short-wave (wavelengths smaller than the ion gyroradius) convective and magnetostatic excitations in a plasma with finite ion pressure, are obtained. The thermal fluctuation spectra are not affected with the mode nonlinear interaction. The growth of the parameter β_i results in the decrease of the convective spectrum intensity and renormalized width. The renormalized widths of potential (density) and magnetostatic fluctuation spectra determined by the relevant damping coefficients, experience nonlinear broadening that is believed to be responsible for transport anomalies. The "magnetostatic" contribution to the nonlocal renormalized kinematic viscosity is negligible for $\beta_e \ll 1$. The finite ion beta values do not influence crucially the anomalous electron heat conductivity, where the relevant coefficient has the Bohm-like scaling.

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PARALLEL DEPOSITION, SORTING, AND REORDERING METHODS IN THE HYBRID ORDERED PLASMA SIMULATION (HOPS) CODE[1]

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ABSTRACT

From a computational standpoint, particle simulation calculations for plasmas have not adapted well to the transitions from scalar to vector processing nor from serial to parallel environments. They have suffered from inordinate and excessive accessing of computer memory and have been hobbled by relatively inefficient gather-scatter constructs resulting from the use of indirect indexing. Lastly, the many-to-one mapping characteristic of the depostion phase has made it difficult to perform this in parallel. Our code sorts and reorders the particles in a spatial order. This allows us to greatly reduce the memory references, to run in directly indexed vector mode, and to employ domain decomposition to achieve parallelization. In this hybrid simulation the electrons are modelled as a fluid and the field equations we solve are obtained from the electron momentrum equation together with the pre-Maxwell equations (displacement current neglected.) Either zero or finite electron mass can be used in the electron model. The resulting field equations are solved with an iteratively explicit procedure which is thus trivial to parallelize. Likewise, the field interpolations and the particle pushing is simple to parallelize. The deposition, sorting, and reordering phases are less simple and it is for these that we will present detailed algorithms. We have now successfully tested the parallel version of HOPS in serial mode and it is now being readied for parallel execution on the Cray C-90. We will then port HOPS to a massively parallel computer, in the next year.

[1]Work performed under the auspices of the U.S. Deparment of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48

LOCAL IDEAL STABILITY OF REALISTIC FIELD-REVERSED CONFIGURATION (FRC) EQUILIBRIA*

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Experimentally realistic FRC equilibria have both racetrack separatrix shape *and* hollow current profile.[1] The tilting stability of such equilibria has only recently been analyzed; they were found to be ideal-MHD stable to tilting for many cases.[2] The present work reports on the stability of local modes, specifically interchange and ballooning, for racetrack-hollow equilibria. These modes may be responsible for the profile consistency observed in FRC experiments.[1] Local ideal stability can be analyzed using the familiar energy principle of Bernstein, et al.[3] For FRC equilibria, the local mode assumption allows each poloidal flux line to be treated independently. Moreover, the analysis reduces to a simple one-dimensional eigenvalue problem where the independent variable is distance along the flux line. Thus the local mode behavior can easily be solved--flux line by flux line--to get both the eigenvalues (growth rate, or mode frequency) *and* the true spatial structure of the mode disturbance. Analytic racetrack-hollow equilibria are used in the stability analysis. Solutions for both interchange and ballooning modes will be presented. The stability will be characterized in terms of the racetrack index and current profile index, quantitative indices that define these two equilibrium attributes. The possible role of local modes in the appearance of profile consistency will be discussed.

*This work supported by the Department of Energy

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Changes in the Tokamak Current during MHD Activity

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The conservation of magnetic helicity, $K=\int \mathbf{A}\cdot\mathbf{B}d^3x$, determines whether MHD activity increases or decreases the net plasma current I in a tokamak. During the relaxation of a narrow unstable region, the change in the plasma current is approximately

$$\Delta I = (\Delta k_i)(\Delta\eta/\eta)/4.$$

with Δk_i the change in the initial parallel current distribution, $k=j_{\parallel}/B$, and $\Delta\eta$ the change in the resistivity across the region. The resistivity normally increases outward, so $\Delta\eta$ is positive. A centrally peaked current profile has a negative Δk_i, and current is lost during a relaxation. If the initial current profile is hollow, Δk_i is negative in the central region, and the current can increase. The loss or gain of current can make a substantial correction, ≈20%, to the current associated with the bootstrap effect or the current drive systems. In particular there is some advantage in off-axis current drive. But, MHD relaxations near the plasma edge, where the current density is dropping and the resistivity is rising, reduce the current. These results are derived by noting that the rate of helicity destruction is given by $2\int \mathbf{E}\cdot\mathbf{B}d^3x$. The parallel Ohm's law implies $\mathbf{E}\cdot\mathbf{B}=\eta(\mathbf{j}\cdot\mathbf{B}-k_aB^2)$ with k_a the part of the current distribution associated with the bootstrap or driven currents. Ohm's law can be rewritten before the relaxation as $V=\eta_c(k_i-k_a)$ with V the loop voltage and $\eta_c=\mu_0(G+\iota I)\eta$. The poloidal current outside a magnetic surface that contains toroidal flux ψ is G, ι is the rotational transform, and I is the toroidal current inside the ψ-surface. MHD activity does not change the rate of helicity destruction but flattens the current distribution into a constant k_0. This implies that $k_0=(\int\eta_c k_i d\psi)/(\int\eta_c d\psi)$ with $k_i(\psi)=k_a(\psi)+V/\eta_c$. The plasma current is related to the current distribution by $I=\int k d\psi$. With these equations on can trivially derive the approximate expression for change in the current, ΔI. Work supported by the U.S. Department of Energy under grant DE-FG05-84ER53176.

Numerical Simulation of Drift Turbulence in the Presence of Sheared Flows Parallel and Perpendicular to the Magnetic Field*

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A two-dimensional spectral fluid simulation code is used to study collisional and parallel sheared flow ($V_{\|}$) driven drift wave turbulence and investigate the effects of both poroidal and toroidal shear flows on drift turbulent fluctuations. The background velocity profiles $V_{\|}$ and V_y are allowed to evolve with time and a neo-classical term is added to the evolution of the $V_y(x,t)$ and $V_{\|}(x,t)$ profiles. The results show that with inclusion of the neoclassical term, the background velocity profiles $V_{\|}$ and V_y rapidly generate strong shear flow which significantly suppresses turbulent fluctuations and reduces the Reynolds stress $\langle V_x V_y \rangle$ and the flux $\langle V_x V_{\|} \rangle$. The vorticity equation is considered with and without the presence of a scalar nonlinearity due to the $T_e(x)$ profile.

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NON LINEAR DRIFT WAVE TURBULENCE

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Many features of a drift wave turbulence are in agreement with the measurements of fluctuations and transport in Tokamaks . However, the traditional model of a drift wave driven by trapped electrons fails in explaining some well reproducible experimental behaviors. First, the linear threshold is not always reached. Indeed, each Fourier mode propagates from its resonant surface, where it is energetically fed by electrons, towards ion Landau resonances, where it is damped. This structure exists if the energy balance is reached, leading to a restrictive threshold if the electron feeding is not homogeneous. Second, the increase of diffusion coefficients towards the edge and the similarity of all those coefficients for all species, including impurities, are hardly explained within the frame of a quasilinear approach. A convincing interpretation of particle pinch velocity is even more difficult to find.

In this work, we emphasize that this picture could be drastically changed by non linear radial localization of Fourier modes near their associated resonant surfaces. Such a localization would enhance the coupling between modes and electrons, including circulating electrons, and therefore decrease the turbulence threshold. In non linear regime, a mode focusing can be due to non linear parallel Landau resonances or to mode coupling through the ion dynamics. Non linear Landau resonances still involve particle velocities, so that the transport of light and heavy impurities should remain different in this case. On the contrary, strong localization due to mode coupling will imply a similar behaviour of ions and impurities which interact with modes through non linear resonances at nearly zero frequency. If the mode propagation is ensured by ion Larmor radius effects, such a state can exist if the width of the electron layer scales as the ion Larmor radius [1]. It is shown in this work that such a localization effect is possible through a soliton-like effect. Moreover, it is also numerically demonstrated that such a turbulence can propagates over macroscopic scales in transient situations. In a stationary regime, it can also exhibit correlations over large distance even if each Fourier mode is strongly localized near its resonant surface, leading to a non-local behavior. This last feature has consequences for the transport scaling.

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Global Alpha-Alfvén Wave Dispersion Relation and Rosetta Stone*

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Alfvén waves, such as the TAE and GAE, can be driven unstable by hot particle Landau effects (e.g., by alpha particles). As an aid to treating and understanding these modes, here we develop an extension of the standard MHD energy principle, which incorporates both the MHD and Landau features. We also call this a global dispersion relation since it reduces to the local dispersion relation in the slab limit. This equation follows from the vorticity evolution equation (a version of $\nabla \cdot \mathbf{j} = 0$). By retaining terms that would ordinarily be omitted after integrating by parts, one can incorporate continuum damping into the global dispersion relation. These results are useful numerically, even for initial value codes, because they provide a useful diagnostic tool to partition the growth rate as a function of radius and mode number into its constituent components: growth due to alpha particles, Landau damping due to electrons and ions, and continuum damping. It is often assumed that the eigenfunctions and real part of the frequency are only weakly affected by kinetic effects such as Landau damping. This means one could utilize the global dispersion relation to quickly survey sensitivities to

- full Maxwellian versus N-Pole approximations
- temperature gradients and $T_\perp \neq T_\parallel$
- full velocity space dependence of magnetic drift
- slowing down distribution vs Maxwellian.

Even when the assumption about the eigenfunctions and the real part of the frequency fails, the use of the global dispersion relation as a diagnostic should give insight into why the failure occurs.

These linear considerations are important, even for nonlinear studies, since formulation and understanding of the latter usually requires considerable insight into the linear processes. Future nonlinear comparison of these fluid-type calculations and guiding center simulations will benefit from the observation that both approaches can be developed from the gyro-kinetic equation. We have developed a Rosetta stone that allows one to quickly identify corresponding terms in the gyro-kinetic equation, vorticity evolution equation, extended energy principle or global dispersion relation, and the slab dispersion relation. We have supplemented this with a terminology Rosetta stone since some of the individual terms go by as many as seven names. Both sides of this Rosetta stone will be displayed.

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Vorticity Model of MHD Jets and Conservation of Canonical Circulation

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The MHD equation of motion is

$$\rho\left(\frac{\partial \mathbf{U}}{\partial t}+\mathbf{U}\cdot\nabla\mathbf{U}\right)=\mathbf{J}\times\mathbf{B}-\nabla P+\rho\nu\nabla^2\mathbf{U}$$

where ν is the kinematic viscosity. In fusion MHD equilibria the velocity is set to zero leading to the Grad-Shafranov equation which (depending on symmetry assumptions) gives equilibria for tokamaks, RFP's, stellarators, and spheromaks. By assumption, these equilibria are static, i.e., have no flows. It is also possible to have dynamic equilibria (i.e., with steady state flows) where the equation of motion has the time-independent form

$$\rho\mathbf{U}\cdot\nabla\mathbf{U}=\mathbf{J}\times\mathbf{B}-\nabla P+\rho\nu\nabla^2\mathbf{U}.$$

For purely poloidal currents in axi-symmetric geometry (e.g., arcs, z-pinches, plasma erosion opening switches, perhaps astrophysical jets) the flows are purely poloidal and the complete visco-resistive MHD system of equations transform[1] to three coupled scalar equations. These show that axial current gradients generate a vorticity plume which drives jet-like[2] flow away from regions of current constriction and is simultaneously convected with the flow. A two fluid model[3] of the same phenomena shows that for each species the quantity

$$\mathcal{C}_\sigma=\int d\mathbf{l}\cdot(m_\sigma\mathbf{u}_\sigma+q_\sigma\mathbf{A})$$

is exactly conserved; here the line integral is around the minor circumference of a toroidal fluid element. Appropriate linear combinations of $\mathcal{C}_i, \mathcal{C}_e$ give the MHD vorticity and induction equations with Hall[4] terms.

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Sherwood Theory Meeting
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Nonlinear Mode Conversion†

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The phenomenon of linear mode conversion can undergo a qualitative change when one of the modes is weakly nonlinear.[1] Its nonlinear wave-number shift can overcome the dephasing due to plasma nonuniformity if the incident action-flux exceeds a threshold. This process has been called spatial autoresonance. We study a simple model analytically and numerically for all the different physical regimes: positive or negative coupling between the waves,[2] positive or negative energy waves, and positive or negative nonlinearities. Some of these cases have unstable solutions, where convective saturation is replaced by unbounded convective growth, linear with distance.

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CONVECTIVE MOMENTUM TRANSPORT, SHOCK VISCOSITY, AND THE L-H TRANSITION IN TOKAMAKS*

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Convective momentum transport associated with $\mathbf{V}\cdot\nabla\mathbf{V}$ in the momentum equation is calculated for arbitrary values of the poloidal $\mathbf{E}\times\mathbf{B}$ Mach number M_p. Here, $\mathbf{V}$ is the plasma flow velocity. The physics origin of the convective momentum transport is associated with the coupling of the poloidal variation of the viscosity-driven flux to that of the flow velocity in the magnetic surface. When the radial gradient scale length of the plasma velocity is of the order of the ion poloidal gyroradius, ρ_{pi}, the convective momentum transport becomes comparable to the ion viscosity. At $M_p \simeq 1$, the ion viscosity associated with shock—the shock viscosity—approximately balances the convective momentum transport to maintain the lowest-order ambipolarity. In the supersonic regime, when $M_p \gg 1$, the convective momentum transport diminishes if the parallel plasma velocity is small (subsonic). The implications of the effects of shock and convective momentum transport for the previous L-H transition bifurcation theory [K. C. Shaing and E. C. Crume, Jr., Phys. Rev. Lett **63**, 2369 (1989)] are discussed, and an extended bifurcation theory including these effects is presented. It is shown that the experimentally relevant plasma viscosity, *effective plasma viscosity*, is very similar to that obtained without including compressibility effects, even if shock exists.

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NONLINEAR FORMALISM FOR PLASMA TURBULENCE CHARACTERIZED BY TWO DIFFERENT SCALE LENGTHS

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Tokamak plasmas are maintained far from thermodynamic equilibrium by the externally applied sources (heating, current drive). The resulting turbulent states are usually characterized by two different scales: There are large-scale phenomena with low poloidal mode numbers and a radial scale much larger than the typical ion Larmor radius ρ_i (for instance, steady magnetic islands); simultaneously there is small-scale electromagnetic turbulence with large poloidal mode numbers and radial scale of order ρ_i. We develop a nonlinear theory which couples MHD and kinetic effects, assuming that the two scales are well separated. We assume that the particles move in an electromagnetic field which to lowest order can be taken to be quasi-helical near the main rational surfaces. For instance:
$\psi^{(0)} = \psi_{o,o}(r,t) + \psi_{2,1}(r,t)\ \exp(2\theta + \phi)$ near the q(r)=2 surface.
Here r,θ,ϕ are intrinsic flux coordinates associated with an axisymmetric equilibrium, and r labels the equilibrium magnetic surfaces. The amplitudes $\psi_{m,n}$ are assumed to evolve slowly in time so that the kinetic equations can be integrated along particle trajectories in the field $\psi^{(o)}$ which includes the large-scale perturbations. The small-scale (electric and magnetic) turbulence is then treated by quasi-linear theory, yielding turbulent diffusion coefficients which affect the large-scale evolution. As an application we discuss some particular idealized cases.

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Magnetic Field Effects on Ballooning Modes in Classical Fluids

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The analogous phenomena to ballooning modes in plasmas are modes localized to streamlines in classical fluids. We have given these modes a thorough analysis and it is apparent that stable flow fields are the exception rather than the rule. Here we are interested in investigating the effect of the presence of a magnetic field on such instabilities. We do not assume, as is common in tokamak stability studies, that the magnetic energy is much larger than the flow energy. For simplicity we consider an axisymmetric configuration with purely toroidal rotation and with either a purely toroidal magnetic field or a tokamak-like field where, however, we only discuss the magnetic center. We also include the effect of gravity. Such a situation may be relevant to the interior of stars and its simplicity allows the derivation of exact conditions for stability. In the absence of a magnetic field, instability is due essentially to the Rayleigh-Taylor mechanism, and we recover the previously known Høiland stability criterion. If a magnetic field is present the criterion is much more complicated. For a large enough field, all non-axisymmetric modes will be stable. However, there may still be a window of instability for the axisymmetric modes if the Rayleigh-Taylor drive is sufficiently strong. In addition to ideal effects we can incorporate various diffusive effects into the analysis. In the case of fluids there is an O(1) effect on stability even for small diffusivity. Its effect on the magnetized fluid is still under investigation.

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Onset of the Sawtooth Crash*

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A new class of $m = 1$ magnetic islands, describing precursor and snake oscillations, is presented. These islands have bounded current-density distributions, so that their resistive evolution is slow. Conservation of the total flux through the island region, however, results in a critical width such that the current-density diverges and the separatrix collapses at the X-point. This critical width is proposed as a threshold for the onset of the kink-tearing mode. Its value depends on the island's history, but varies inversely with the resistive stability parameter $\Delta'_{1/1}$. A phenomenological evolution model is used to illustrate the sub-critical island dynamics and to compare the present theory to experimental and computational results.

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Partially Linearized Gyrokinetic Simulations with Ion-Ion Collisions*

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The gyrokinetic collision algorithm of Xu and Rosenbluth[1] based on the formalism of Catto and Tsang[2] has been extended and implemented in a partially linearized gyrokinetic simulation code. Both drag and diffusion contributions to the collision operator are retained. This extends the work of Xu and Rosenbluth by including momentum and energy-conserving source terms and by removing the restriction to a single Fourier mode. The scheme approximately conserves energy and momentum locally in a statistical sense. Test cases demonstrating the accuracy of the collision operator and code timings are presented. The additional cost of doing collisions is an acceptably small fraction of the cost of pushing the ions. The implementation of the collision algorithm is first-order accurate in time, which proves to be adequate for weak collisions. As part of using the ion-temperature-gradient (ITG) instability as a test case, the linear dispersion relation for an ITG mode in the local limit with weak collisions has been derived from the formalism of Chang and Callen.[3] We have checked this calculation with an alternative derivation based on an extension of the Hammett-Perkins Landau-fluid model[4] in which both viscosity and thermal conductivity are used to fit the results of a Fokker-Planck kinetic theory.[5] The effect of collisions on the ITG mode at long wavelengths is to increase the linear growth rate and lower the threshold value of the ratio of density to temperature scale lengths. The particle simulations generally confirm the dependence of the growth rate on collisionality and show that the momentum and energy-conserving source terms need to be retained. The ion thermal transport accompanying the ITG instability is increased by collisions. Our experience so far is that the collisional model ceases to be reliable when the collisionality becomes too strong: when the mean-free path of the ions becomes much shorter than the parallel wavelengths of the modes (a regime where logically a fluid code would be more appropriate), errors in the collision algorithm mask the ITG instability.

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

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Stochastic Ripple Losses of Fast Ions on TFTR *

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In full aperture plasmas with low plasma current on TFTR, transport analysis overestimates the fast ion population, with magnetic and kinetic analysis of beam ion stored energies disagreeing by 20% or more. In addition, fast ion edge detectors measure deuterium ions lost; and some TFTR triton burnup experiments did not find as many events as expected.

We are investigating the role of toroidal field stochastic ripple-caused diffusion for these experiments. If these losses are significant, they must be included before interpreting these experiments with theoretical models for energy and particle confinement.

A Hamiltonian-coordinate particle-following code with toroidal field ripple is being used to study losses of alpha particles and neutral beam-deposited deuterium ions for specific TFTR experiments. Applications of this code to a variety of TFTR experiments will be presented.

Approaches for incorporating ripple induced fast ion diffusion into the TRANSP analysis code will be discussed.

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Bulk Ion Gyrokinetic effect in the 3D Hybrid Particle/Fluid Code, MH3D-K*

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The 3-D nonlinear toroidal MHD code, *MH3D*, had been used successfully to predict global 3-D MHD phenomena in tokamaks. Our plan is to systemetically extend this code through stages of realism until it can simulate tokamak discharges including most of relevant physics – a Numerical Tokamak. As the first step, we reported that gyrokinetic hot particles have been included into the code, which is now called *MH3D-K*.[1]

In the current stage, we are extending the code to include bulk ion gyrokinetic effects. Quasi-neutrality and massless electron fluid are assumed. The bulk ion pressure tensor P is coupled through

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

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

where $\mathbf{v}_{\mathrm{E}} = [\mathbf{v} - (m/\rho q)\mathbf{J}]_{\perp}$ with $p_e = 0$. The density ρ is obtained from particles. One way to treat the $\nabla \cdot \mathsf{P}$ term is to use $\mathsf{P} = \mathsf{P}^{\mathrm{CGL}} + \Pi_{\mathrm{g}}$, and obtain $\mathsf{P}^{\mathrm{CGL}}$ from particles while including $\nabla \cdot \Pi_{\mathrm{g}}$ explicitly in momentum terms using the 'gyroviscous cancellation'. The other way is to calculate P to higher order in FLR from the particles.

We have also developed a new method to linearize a particle code by following two sets of particles, one the unperturbed particles and the other the purturbed particles. This method drastically reduces the noise due to the particle statistics in the linear phase.

Linear and nonlinear studies of 3D kinetic balooning instabilities will be presented.

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1993 SHERWOOD INTERNATIONAL FUSION THEORY CONFERENCE

An Explanation For The Cause And Energy Source Of Solar Flare Production — A new mechanism of thermonuclear reaction

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A new mechanism of thermonuclear reaction was first presented in the preceding papers[1-3]. It shows that a small amount of thermonuclear reaction can take place in dense,low temperature($T<1\times10^5$ K) plasmas,such as in the surface and atmosphere of the Sun and stars,in the core of the giant planets and the Earth,etc.It can be used to explain some mysteries and puzzles in astrophysics,such as the energy source in large planets and their mass-luminosity relation[1], the solar neutrino problem,[2,3] etc.,and also to interpret a number of abnormal fusion phenomena observed in laboratories.In superhigh temperature plasmas,it is in good agreement with the old thermonuclear reaction mechanism first presented by Gamow and Bethe. In dense,low temperature plasmas, its fusion reaction rate $<\sigma v>$ is about tens of orders of magnitude higher than that of the old mechanism and is increased rapidly with an increase in temperature. Under the action of some specific,strong magnetic fields in the atmosphere of the Sun on its local plasmas,the density and temperature in the plasmas are increased as a result of magnetic confinement and constraint,that causes a rapid increase in fusion reaction rate $<\sigma v>$ and in fusion energy which continues heating the local confined plasmas,by which the temperature in the plasmas is rapidly increased again. Thus the energy-generation rate and fusion energy in the plasmas are also continuously increased until their kinetic pressure is enough higher than the magnetic pressure.Finally a flare will be burst therein. From this mechanism it is predicted that the configurations of magnetic fields causing the flare are similar to those in magnetically confined plasmas in laboratories,so that the basic properties and features of flares,and their size,are strongly dependent on the configurations of magnetic fields in flare region and their strength. All this has yet to be tested further and observed in detail.

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Exceeding the Brillouin Limit:

*A Novel Path to Inertial-Electrostatic Confinement of a Single-Species Plasma**

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Abstract

The physics limiting the density of a cold nonneutral plasma will be presented. It will be shown that when a flow has no strain, the instantaneous maximum number of charges that can be stored within a fixed boundary is equal to the total magnetic field energy within divided by the relativistic rest energy of a single charge. A higher limit can be supported by the presence of a deviatoric strain in the flow. Brillouin flow equilibria with arbitrarily high values of the Brillouin ratio, leading to the possibility of pure inertial-electrostatic confinement of nonneutral plasmas, will be demonstrated.[1]

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Symbolic Signal Processing*

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Complex dynamic processes exhibit many complicated patterns of evolution. How can we recognize all these patterns using only output (observational, experimental) data without prior knowledge of the equations of motion? The powerful method for doing these is based on symbolic dynamics:

1. We present output data in symbolic form (trial language).
2. Topological and metric entropies are constructed.
3. We develop algorithms for computer optimization of entropies.
4. By maximizing entropies we are able to find the most appropriate symbolic language for the purpose of pattern recognition.
5. We have tested this method using variety of dynamical models from nonlinear science.

We are in the process of applying this method for analysis of MHD fluctuations in tokamaks.

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Two-Dimensional Numerical Simulation of Drift Waves and Trapped Ion Modes

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Drift waves (DW) and trapped ion modes (TIM) are concurrently simulated by a two-dimensional pseudo-spectral nonlinear code with a dense wavenumber grid. This extends our previous work which treated DW and TIM turbulence separately [1,2]. The model includes curvature effects and collisionality. Two fluids are used to represent the dynamics throughout wavenumber (k)-space. Physically, the DW and TIM equations apply to disjoint regions of k-space characterized by $\omega \gg \omega_{\mathrm{b}}^{\mathrm{i}}$ and $\omega \ll \omega_{\mathrm{b}}^{\mathrm{i}}$, respectively, where $\omega_{\mathrm{b}}^{\mathrm{i}}$ is the ion bounce frequency. Here, the boundary is modeled by a single, appropriate $k_y \rho_{\mathrm{s}}^{\mathrm{i}}$. The DW and TIM fields can only interact via the $E \times B$ convective nonlinearity. The effect on the net diffusion is of interest. The DW turbulence when considered separately has a spectrum peaked at wavenumbers below the most linearly unstable ones; this implies an inverse cascade mechanism. The TIM are of long wavelength and therefore might contribute significantly to the diffusion if they were driven to large amplitudes either by the linear growth or by the DW turbulence. Our preliminary results show that the net diffusion is not significantly affected by replacing the low k_y DW dynamics by TIM equations. The spectrum is suppressed inside the TIM region compared to having no TIM (DW extending to $k_y = 0$) in part because the lowest k_y TIM are collisionally damped.

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On Magnetohydrodynamic Modes Driven by Energetic Particles in Tokamaks†

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A theoretical approach, based on the generalized ballooning-mode formalism, has been developed to analyze the continuum damping of discrete toroidal Alfvén eigenmodes (TAE) in finite-β tokamak plasmas. Specific damping rates have been calculated for the (s, α) model equilibrium. In particular, it is found that there exists critical α values, α_c, such that, as $\alpha \rightarrow \alpha_c$, TAE would be stabilized due to enhanced continuum damping. On the other hand, we have also examined instability driving mechanisms including finite orbit effects of the energetic particles. Generic "fishbone-like" dispersion relations have been derived for both the kinetic ballooning modes (KBM) and TAE. We note the existence of the energetic-particle branch. For the low-frequency KBM, the energetic-particle branch typically dominates the MHD branch. Implications to TAE will also be discussed.

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An Analytically–Based Method for Rapid Evaluation of MeV Ion Loss in Tokamaks with Low–n Perturbations

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Recent work[1-3] has developed an analytic theory for the stochastic transport of passing MeV ions due to low–n magnetic perturbations, valid for frequencies from $\omega = 0$ to $\omega \sim \omega_{TAE} \sim 100$ kHz, and for modes with multiple harmonics and nontrivial radial structure, which predicts stochastic thresholds in agreement with guiding-center (GC) results. Obtaining GC results is time consuming, typically requiring hours of computer time to obtain loss results for a single point in parameter space. Along with earlier theory[4] developed for the stochastic transport of trapped particles in such perturbations, this theory gives the basis for a far more rapid means of numerically assessing energetic ion loss in a given configuration, somewhat akin to the RIPLOS code[5] for rapid evaluation of loss due to TF ripple. We present the details of implementing such a code, now being developed. The implementation also raises some further theoretical issues. The currently available stochastic thresholds for passing and trapped particles are not the same,[2] and an analytic understanding of the transition between them awaits development.

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Eikonal theory of gyroresonant Case-van Kampen modes in tokamak geometry

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We consider the generalization of the Case-van Kampen analysis, originally applied to the linearized Vlasov equation in 1D, to gyrokinetics in tokamak geometry. In previous work we have shown how to use the one dimensional Case-van Kampen approach, in conjunction with the Bateman-Kruskal WKB algorithm[1], to compute the collective wave spin-off (to the minority-ion Bernstein wave) and gyroballistic continuum for minority gyroresonant absorption in a 1D slab model[2]. Here we discuss how to extend these results to tokamak geometry, including trapped particle effects. The major new element is that in higher dimensions the WKB Case-van Kampen eigenfunctions do not form an orthonormal set. Extraction of the expansion coefficients for solution of the initial value problem (in k-space) requires the solution of a Fredholm integral equation of the second kind. We discuss approximate solutions of this integral equation in the limit where the minority species is cold and the gyroballistic dispersion relation depends weakly on the invariants associated with the particle gyromotion.

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ANOMALOUS PERTURBATIVE TRANSPORT IN TOKAMAKS DUE TO DRIFT-WAVE TURBULENCE

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We calculate from first principles the incremental transport of particles and heat in the presence of electrostatic drift-wave turbulence in a tokamak plasma. The renormalized nonlinear plasma response function is derived using the Direct-Interaction Approximation (DIA). We obtain explicit expressions for all coefficients of the anomalous transport matrix relating particle and heat fluxes to density and temperature gradients in the plasma. The transport coefficients are about 2 to 4 times larger than predicted by the test-particle approximation. We find that, in the regime of interest, the trapped electrons contribute most to the transport. The anomalous transport matrix calculated in the DIA approximation does not have the Onsager symmetry. Using the parameters of the Texas Experimental Tokamak (TEXT), we evaluate all transport coefficients numerically, as well as the spectrum modulation. The relation between the theoretical results and the experiments is discussed. We also calculate the transport coefficients in the presence of drift-Alfvén-wave turbulence, i.e., taking into account the magnetic field fluctuations. The magnetic terms are important for the transport by circulating electrons, but leave the transport by trapped electrons unaffected. Finally, we show that the transport of impurity particles is given, to first order in the impurity concentration, by the test-particle result.

Neutral-Plasma Interaction in the Long Mean-free-path Limit*

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For the neutral-plasma interaction problem, we obtain a Green's function which is valid for all mean-free-paths (mfp). We include ionization, charge-exchange (CX), a drifting Maxwellian ion distribution, and a half-Maxwellian neutral source at the plasma-wall boundary. In the long CX mfp limit, relatively simple recursive solutions are obtained directly without the use of singular eigenfunctions.[1] We calculate the neutral density, heat flux, and drag on the ions. In the short CX mfp limit, we recover our earlier Chapman-Enskog solution.[2] The possibility of using this Green's function to develop faster neutral transport codes is being explored.

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SELF-CONSISTENT THEORY OF MAGNETIC DIFFUSION AND THE TURBULENT DYNAMO

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The concepts of turbulent diffusion of magnetic fields and the α-effect dynamo are now classic in MHD turbulence. However, both notions neglect the back-reaction of small scale turbulent magnetic fields which are rapidly amplified from a large scale seed by fluid turbulence. Recent computational studies by S. Vainshtein, et. al., suggest that such small scale back-reaction may inhibit magnetic diffusion and the α-effect. Here, we investigate these predictions analytically.

In 2D, magnetic diffusion is found to be inhibited. The physical process at work is the rapid growth of small scale magnetic energy to the point that the inverse transfer of mean square magnetic flux can compete against the tendency of the fluid to "chop-up" and diffuse the flux. As a result, relaxation and transport are inhibited. In 3D, a similar process produces a back-α-effect which competes against and suppresses the hydrodynamic α-effect! However, the turbulent diffusion of magnetic fields <u>does</u> survive in 3D. The implications of these results for dynamo theory will be discussed.

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A 3D Fokker-Planck Code for Studying Transport Along the Magnetic Field Lines

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There are numerous situations in tokamak plasmas which are in an intermediate collisional regime, where the mean-free path is comparable to plasma parameter scale-lengths along the magnetic field lines. To study this class of problems we are developing a new code $CQL_{\|}$ starting from the Fokker-Planck code CQL3D [1], which solves the Fokker-Planck equations with two velocity coordinates (u, momentum per rest mass, and θ, pitch-angle) and the radial spatial coordinate. In $CQL_{\|}$, the spatial coordinate is now along the magnetic field lines $\underline{B}/B$. The diverse features of CQL3D are kept: multi-species, nonlinear, relativistic, toroidal geometry, non-circular flux surfaces. In addition, we shall also allow for arbitrary magnetic field variation and extend the code to non-up/down symmetric plasma cross-section. The equation is coupled to Poisson's equation in order to calculate the electric field iteratively in a consistent way. Finite differences and an alternating direction implicit method (ADI) are used to solve the equation.

The model will be presented together with the different boundary and geometrical conditions, as well as the different source terms which can be included. Some of the possible immediate applications are in divertor physics: sheath problem with a consistent electric field couple to non-Maxwellian distribution functions, presheath transport, coupling between presheath and sheath, new neoclassical effects of parallel gradients in an inhomogeneous magnetic field, and parallel transport of impurities.

Different source terms can be included simulating, for example, the flow of neutrals from the divertor with ionization and charge-exchange processes, the entrainment of impurities by plasma flow to the divertor plate (source added at mid-plane of cross-section), the premature loss of ions due to their finite Larmor orbits when the angle of incidence of the field with the plate is very small. The effect of rf on parallel transport toward the divertor can also be studied using the quasilinear terms.

Latest progress and near future applications will also be described.

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1993 Sherwood Theory Meeting

THE VH-mode at JET

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Some of the high performance JET H-mode discharges, in particular those obtained during the series of experiments leading up to the PTE, make an additional transition to a mode of enhanced confinement, after the transition from L- to H-mode. This transition is usually coincident with the disappearance of the ELMs observed in the H-mode phase. The energy confinement time in this enhanced mode reaches values a factor of 2 above the value of the ITERH92-P scaling and a factor of 3 above that of the Goldston L-mode scaling. The high confinement is associated with reduced energy transport near the edge.

We report on the stability of these discharges against ideal ballooning modes using a finite aspect ratio formulation which has been extended to include resistive instabilities. We show that the lower and upper ballooning stability regions, corresponding, respectively, to low and high pressure gradients coalesce, thus allowing the higher pressure gradients observed. This coalescence, which leads to the disappearance of the unstable zone separating the two regions, will occur near the magnetic separatrix, provided that the surface-averaged current exceeds a certain critical value. Although the edge current is low during the ELM phase and the second stability region is not accessible, high edge current develops rapidly at the end of the ELM phase and the second stable region becomes accessible. At the same time the edge pressure gradient increases dramatically, moving into the second stable region, as the energy confinement time increases above that of the H-mode. The fraction of plasma volume where this second stable access occurs increases steadily, from the edge inwards, during the evolution of the enhanced confinement mode. Whilst the steep density and temperature gradients are associated with the H-mode, the enhanced mode confinement appears to be a consequence of the broadening of these steep gradients. The local transport evolution calculated from the TRANSP code shows a reduction in ion diffusivity at the onset of the ELMs, with the bootstrap current increasing continuously through this phase of the H-mode into the ELM-free phase; this increase of the bootstrap current leads to the appearance and broadening of the region with second stable access. These results point to the existence of a VH-mode type of high confinement at JET.

Stationary 3D Vlasov Plasma Equilibria.*

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

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Neoclassical kinetic theory near the edge of a diverted tokamak plasma.*

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In a diverted plasma, the poloidal magnetic field has a strong poloidal variation, aproaching zero near the X-point. Typically, neoclassical theory is based on ordering assumptions about the 3 characteristic frequencies present in the problem: streaming, collisions and drift. In a circular geometry, the streaming frequency is constant, while the drift frequency has a sin(θ) variation. In a shaped plasma, the streaming frequency also has a poloidal variation. The ordering is now established by the amplitude of these frequencies. With a model poloidal flux function, we solve the drift kinetic equation inside, but near, the separatrix. Both the plateau and collisional regime are considered. Ion rotation rates, and their poloidal variation, are calculated. It is shown that the standard neoclassical rotation predictions still hold, when correctly interpreted. Other neoclassical fluxes are calculated as well.

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3-D Monte Carlo simulations of fast ion confinement for stellarators with the radial electric field

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The role of the radial electric field, E_r, in energetic trapped particle confinement was investigated in non-axisymmetric toroidal devices with orbit following Monte-Carlo beam ion thermalization codes. A comparative study was performed [1] in Wendelstein VII-A (IPP, Garching) and Heliotron E (Kyoto University, Uji) for explaining efficient heating achieved with perpendicular neutral beam injection. "Re-entering" [2] of fast ions was examined in the presence of the E_r field with multiple assumptions on the loss boundary of particles. Monte Carlo simulations showed that an inward E_r field improves heating efficiency in WVII-A but tends to deteriorate it in Heliotron E. This difference was interpreted in terms of fast-ion loss regions induced by two different branches of the $\vec{E}\times\vec{B}$ drift resonance. The efficient heating in WVII-A was explained with a counter-side shift of trapping edge of *resonant-banana orbits* due to the $\vec{E}\times\vec{B}$ resonance. The enhanced fast-ion loss in Heliotron E was explained by the other resonance that occur between the $\vec{E}\times\vec{B}$ drift and the poloidal drift of helically trapped ions. However, the resulting *resonant-superbanana loss* was confirmed to be small when the vacuum vessel was used as the boundary. Effects of re-entering on ion-heating rate and charge-exchange loss were also clarified. It is concluded that the efficient perpendicular injection heating observed in Heliotron E is compatible only with Monte-Carlo simulations that take re-entering of fast ions into account. Simulation results for recent perpendicular injection experiments in CHS (NIFS, Nagoya) [3] will also be presented.

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Feasibility of Driving Perpendicular Rotation in Core Plasma by Off-Axis Neutral Beam Injection to Suppress Microturbulence

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Various aspects pertaining to driving perpendicular rotation in core plasma with neutral beam injection to suppress microturbulence are discussed. The assessment is based on the premise that a critical perpendicular velocity shear of order C_s/L_s is required to effect significant turbulence suppression [1,2]. The equilibrium of a tokamak plasma rotating poloidally at such high frequencies is examined from drift-kinetic theory. It is shown that a substantial fraction of trapped particles is now detrapped. The calculation also shows that viscous damping from magnetic pumping falls off as the square of the poloidal speed [3]. This reduction in viscous damping makes more efficacious the driving of large poloidal flows from off-axis neutral beam injection. The feasibility of exceeding the critical velocity shear is assessed, both for present day tokamaks as well as for reactor parameters. The magnetohydrodynamic stability of tokamak plasma rotating at high speeds with respect to Kelvin-Helmholtz and interchange modes is assessed.

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The H Confinement Regime as a State of Topological Incompatibility with Transport Inducing Normal Modes

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The onset of the so-called H-regime for plasma confinement is considered as resulting from the transition to a state where the main microinstabilities that can affect transport at the edge of the plasma column cannot be excited as normal modes[1] but as transient perturbations at best. The inability of these instabilities to survive as normal modes is shown to be the result of the combined effects of the magnetic field shear[2] and of the $\underline{E} \times \underline{B}$ rotation frequency shear due to relatively sharp gradients of the transverse electric field that can be induced by a variety of factors.[3]

The most resilient case is that of the ion temperature gradient driven mode which was known to survive the effect of the magnetic shear alone by acquiring a sharp, narrowly localized radial profile[4], around the relevant mode-rational surface. When a relatively strong shear of the electric field is introduced, bound modes, that can satisfy the appropriate boundary conditions, can no longer be found. The solutions of the relevant dispersion equation have a typical oscillatory profile, as a function of the radial variable and, in addition, do not lend themselves to be superimposed to form wave packets that could reach a significant amplitude[5], before they disintegrate.

Therefore, the criterion that we find, for the transition to a state where normal modes are not allowed to exist, is

$$\frac{v_E r_T}{v_s r_E} > \left(\frac{r_T}{r_n}\right)^{3/2} > \left(\frac{r_T}{L_s}\right)^{3/4},$$

where v_E is the $\underline{E} \times \underline{B}$ velocity, v_s the ion sound velocity, and r_e, r_n, r_T, L_s are the scale distances for the $\underline{E} \times \underline{B}$ velocity shear, the local density gradient, the ion temperature gradient, and the magnetic shear, respectively.

We point out that the disappearance of normal modes in the presence of sufficient shear of the $\underline{E} \times \underline{B}$ velocity had been considered earlier in the context of the Earth's ionosphere.[6]

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Time-advance Algorithms based on Hamilton's Principle*

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Time-advance algorithms based on Hamilton's variational principle are being developed for application to problems in plasma physics and other areas. Hamilton's principle was applied previously to derive a system of ordinary differential equations in time whose solution provides an approximation to the evolution of a plasma described by the Vlasov-Maxwell equations.[1] However, the variational principle was not used to obtain an algorithm for solving the ordinary differential equations numerically. The present research addresses the numerical solution of systems of ordinary differential equations *via* Hamilton's principle. The basic idea is first to choose a class of functions for approximating the solution of the ordinary differential equations over a specific time interval. Then the parameters in the approximating function are determined by applying Hamilton's principle exactly within the class of approximating functions. For example, if an approximate solution is desired between time t and time $t + \Delta t$, the class of approximating functions could be polynomials in time up to some degree. The issue of how to choose time-advance algorithms is very important for achieving efficient, physically meaningful computer simulations. Our objective is to reliably simulate those characteristics of an evolving system that are scientifically most relevant. Preliminary numerical results will be presented, including comparisons with other computational methods.

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DT Simulation of ICRF Heated Supershots in TFTR using TRANSP*

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Experiments using a mix of deuterium and tritium (DT) are planned for TFTR to study plasma conditions near break-even and to study the effects of fusion α particles. The principal goal of ICRF heating on TFTR is to enhance performance of plasmas during the DT physics phase of operations[1]. Strongly centralized ICRF heating may play a critical role in obtaining high $Q_{D\text{-}T}$ and high β_α operation in TFTR as well as in future fusion reactors. ICRF heating of a dilute minority species leads to the formation of an energetic ion population which, according to existing theories, can act as a stabilizing agent against m=1 internal kink instabilities which are thought to cause sawtooth oscillations in tokamak plasmas. Indeed, complete suppression of sawtooth oscillations has been observed for several energy confinement times during ICRF heating experiments on JET and TFTR. Furthermore, strong central electron heating has also been observed in these experiments. The corresponding rise in the central electron temperature translates into an increase in the slowing down time of either neutral beam or alpha particles in the discharge. Preliminary DT simulations of the experimental results in DD plasmas were performed with the TRANSP code. The results indicate that the β_α would be increased for plasmas both with and without sawteeth. Comparison is made between H and ^{3}He minority heating cases. In the H minority case, the application of ICRF experimentally results in enhanced neutron emission, despite the fact that shots exist for which the electron temperature is the same whether or not the ICRF is applied. TRANSP simulations indicate that this is due to second harmonic heating of the D beam ions.

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Dynamics and Control of m=2 Islands in TEXT

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In this paper, we describe two experimental and theoretical studies of m=2 islands in the TEXT tokamak. The first study describes the suppression of m=2 islands by electron cyclotron heating, and the second describes the behaviour of the rotation frequency of m=2 islands as a function of the island width in the presence of a radial electric field.

Electron Cyclotron Heating (ECH) is used to suppress m=2 MHD oscillations in TEXT. The location of ECH power deposition is controlled by a movable antenna. The suppression of MHD activity is seen to be effective when the ECH beam is directed towards the vicinity of the q=2 surface. The experiment is simulated using the 3-D cylindrical resistive MHD code DEBS. For fixed total plasma current, the saturated m=2 island width is found to depend on the value of q_0. The simulation suggests that the observed saturated m=2 island width (without ECH), which is typically 25% of the minor radius, corresponds to $q_0 \sim 1.3$. The suppression of the island in the presence of ECH is attributed to the flattening of the current profile across a region wider than the width of the island, and a simultaneous reduction in the value of q_0. It is observed in some cases that the m=2 activity does not resume even after the ECH pulse is turned off. In these cases, the resistive MHD simulation confirms that the current profile obtained at the end of the ECH phase is not unstable nonlinearly to m=2 islands, and shows no tendency to return to the pre-ECH form by a resumption of resistive MHD activity.

The second study is motivated by recent observations of the rotation frequency of m=2 islands versus the island width in TEXT (Brower et al. 1992). These observations show that m=2 modes do not lock in TEXT but continue to rotate with a frequency that decreases with increasing island width. There is a driving radial electric field in TEXT, though this field does become small for large islands. This radial electric field, and the resultant radial current density, can drive poloidal as well as toroidal rotation, despite the retarding effects of magnetic pumping and the induced eddy currents in the resistive walls. Thus plasma flows remain, though at small magnitudes, and prevent mode-locking. Numerical simulations of the TEXT data using the DEBS code, including the effects of plasma flows and resistive walls, will be presented.

DIFFRACTION AND GAUSSIAN $n_{||}$ EFFECTS IN LOWER HYBRID WAVE PROPAGATION IN TOKAMAKS

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In lower hybrid (LH) wave absorption in tokamaks, one is confronted with the spectral gap problem: what are the physical mechanisms that allow the plasma electrons to absorb the LH waves - especially since the initial parallel wave phase velocity is so much higher than the electron thermal velocity? We examine two possible mechanisms: (i) scattering from density and magnetic fluctuations, and (ii) diffraction.

Scattering from fluctuations is examined by extending the Bonoli-Ott[1] Monte Carlo code to incorporate both magnetic flucutations[2] and the effects of Gaussian initial wave $n_{||}$.

Diffraction effects are examined following the work of Pereverzev[3]. In this approach, one takes directly into account the plasma inhomogeneities by performing an orthnormal expansion in localized wavepackets. The group velocity of the wave is shown to be determined by standard ray trajectory methods, but for narrow beams one can obtain diffraction information perpendicular to the group velocity. The electrostatic calculation of Pereverzev is extended to incorporate electromagnetic effects. Electromagnetic effects can be expected to be important if launched nll are close to the critical value of wave accessibility, as well as for ion plasma heating.

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Finite Mean-Free-Path Effects in Tokamak Scrape-Off Layers*

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When the electron mean free path (mfp) becomes bigger than about 1/10 of the parallel electron-temperture gradient scale length, it is well-known that departures from the Spitzer thermal conductivity become important. These departures are commonly modelled by limiting the parallel heat flux $q_{\parallel}$ to an empirically determined fraction of $nT_e v_{te}$ where v_{te} is the electron thermal speed. The use of flux limit expressions in 2-D scrape-off layer (SOL) modelling codes leads to the qualitatively correct result that the electron temperature drops along a field line as heat is leaked by radial transport[1], but perhaps for the wrong reasons. In particular the flux-limiting form is demonstratably incorrect in the long-mfp limit. Here we re-examine this issue. Recognizing that the heat flux is carried by superthermal electrons, we formulate a linearized 3-D Fokker-Planck problem much in the spirit of the papers in Ref. 2. We depart from these treatments by noting that, for typical SOL parameters, the superthermal particles classically carrying the bulk of the heat flux have long mean free paths and are in the loss cone, and so are absent from the distribution function. We argue that this is a key feature which will reduce the heat flux below that calculated in Refs. 2. We outline several strategies for reducing the Fokker-Planck equation to analytically tractable and/or computationally more tractable forms. In particular, we discuss a diffusion model for the isotropic part of the distribution function, its numerical implementation, and limits in which approximate analytic solutions can be obtained. We also present a heuristic model for the heat flux that accounts for the physical effects discussed above and which has the correct asymptotic limits for small and large mean free path. We compare this model and preliminary analytic and numerical results from the diffusion model with Monte Carlo simulations.

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Simulating Density and Temperature Modulation in Oscillating Gas Puff Experiments*

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Previous transport simulations[1,2] of the oscillating gas puff on TEXT[3] focused on fitting the density modulation. We investigated coupled particle and energy transport using models with adjustable off-diagonal elements (flux terms proportional to ∇n_e and ∇T_e). These studies employed dissipative trapped-electron scaling in the core and fixed *ad hoc* transport coefficients in the periphery. Comparing with the amplitudes and phases of the experimental perturbed quantities, we attempted to quantify the need for inward pinch terms in the models. None of the models were able to fit both the radial profile and the density scaling of the n_e modulation.

Here we employ a more general quasi-theoretical transport model that extends to the periphery, *i.e.*, transport coefficients that are adjustable powers of dimensionless parameters, plus profile adjustments somewhat reminiscent of Tang's profile-consistent microinstability model.[4] With various gyro-Bohm-like scalings, we can fit the experimentally observed density modulation provided a pinch term is included in the density flux.

The observed temperature modulation, however, is much smaller than that of the density and cannot be reproduced by any of the models we have used so far. It should be noted that some suggested models involving powers of density and temperature can lead to instabilities, resulting in the collapse of either T_e or n_e.

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Reconnection of Magnetic Field Lines in a Turbulent Flow

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The effect of a turbulent flow on the rate of reconnection of magnetic field lines by a tearing instability is calculated numerically. The reconnection rate is found to be reduced by the turbulent flow. The turbulent flow transfers energy from the growing tearing instability into shorter wavelength electromagnetic modes that are stable. This nonlinear interaction results in a negative, stabilizing contribution to the tearing mode stability parameter Δ' of the long wavelength tearing mode, thereby reducing the rate of reconnection of magnetic field lines by the tearing mode. The numerical results presented contradict the prediction of a turbulence theory of Diamond, Hazeltine, An, Carreras, and Hicks [Phys. Fluids **27**, 1449 (1984)] that a turbulent flow causes an anomalous diffusivity that increases the growth rate of tearing modes.

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LOWER HYBRID CURRENT DRIVE IN THE PRESENCE OF ICRF WAVES *

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Motivated by recent JET results showing an enhancement in the lower hybrid current drive (LHCD) efficiency in ICRF heated plasmas, we have been studying the interaction of lower hybrid generated electron tails with fast Alfvén waves (FAW) and ion-Bernstein waves (IBW). The IBW's are generated by mode conversion, at the hybrid resonance layers inside the plasma, of the externally launched FAW's. Our numerical solutions of the Fokker-Planck equation using CQL3D [1] show that, for the powers used in JET, the FAW cannot significantly modify the LH electron tail and, consequently, does not play a role in the enhancement of LHCD efficiency. Similar analysis for IBW's shows that these waves play an important role in the enhancement of the current drive efficiency. Calculations show that for small $k_{\|}$'s about 20% of the FAW power is mode converted to the IBW's. Previous analysis of the propagation of IBW's [2] has shown that the electric field amplitudes are considerably enhanced as IBW propagate in toroidal plasmas. This compensates for the possibly small fraction of the total input power that mode convertes to IBW's. Furthermore, IBW's interact with electrons off-axis through Landau damping on flux surfaces where LHW's generate currents. FAW's only interact with electrons near the ion cyclotron or ion-ion hybrid resonance layers which, in the case of JET, maybe near the axis of the plasma while the LH waves damp well off-axis. So IBW's are more likely to enhance the LHCD efficiency. In fact, the conditions for which JET shows an enhancement in LHCD efficiency are those for which mode conversion to IBW's occurs. We will present detailed analytical and numerical results in support of the statements made above.

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RANGE OF OBJECTIVES OF THE IGNITOR EXPERIMENT*

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The Ignitor experiment involves an advanced, compact, high magnetic field machine with the purpose of investigating deuterium-tritium (D-T) fusion burning and ignition conditions[1]. Its main goals are:

- to study the containment of the produced α-particles;
- to investigate collective modes and transport processes in D–T fusion burning plasmas;
- to attain fusion burning and ignition at relatively low peak temperature ($T_{io} \simeq T_{eo} \lesssim 15$ keV) and values of the confinement parameter $n_o \tau_E \gtrsim 4 \times 10^{20}$ sec/m^3, thus avoiding the need for reliance on an injected heating system. (Here n_o is the peak plasma density and τ_E is the energy replacement time);
- to study the effectiveness of a suitable ion cyclotron resonance frequency (ICRF) heating system, with $P_{RF} \lesssim 18$ MW, in accelerating the approach to burning conditions, and in controlling the evolution (central peaking) of the toroidal current density profile with the purpose to avoid the onset of possible sawtooth oscillations;
- to test diagnostic systems for burning plasmas;
- to identify new methods for control, heating and fueling of high density plasmas.

Furthermore, the expected plasma parameters, the highly optimized set of poloidal field coils and the availability of a ICRF system and of a pellet injector make Ignitor suitable for exploring

- the subignited, $Q \lesssim 5$ fusion burning, high field physics regime;
- the possibility of producing significant power from D–^{3}He fusion reactions, using ICRF heating to enhance reactivity in a D plasma with a ^{3}He minority;
- the access to the high-β second stability region by operating in a D plasma at low field and plasma current with substantial ICRF heating. In this case the plasma column can be maintained over relatively long times in view of the fact that the Ignitor magnets are cooled down to 30 K. In this respect Ignitor is as suitable as a superconducting facility to explore long pulse operation, while having a set of desiderable geometrical characteristics such as its low aspect ratio.

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RF Enhanced Bootstrap Current with CQL3D

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The bootstrap current in tokamaks is based on the banana magnetization current ($= \varepsilon^{3/2}/B_{\rm pol}\ dp/dr$) of the trapped particles. In neoclassical theory, this is increased by $1/\varepsilon$ due to collisionally-induced (viscous) transfer of parallel momentum from passing to trapped particles on the $-v_\parallel$ side of the distribution and from trapped to passing particles on the $+v_\parallel$ side, giving the bootstrap current [1]. Radio frequency-induced quasilinear diffusion of the electrons can increase the bootstrap current by effectively increasing the scattering across the trapped-passing boundary in velocity space and therefore the viscous coupling between the trapped and passing particles [2]. This process can be modeled using the CQL3D bounce-averaged Fokker-Planck code [3] by modification of the boundary conditions on the distribution function at the trapped-passing boundary: (1) the trapped particles, previously considered in the zero-banana width limit to be symmetrically distributed in $v_\parallel$, are augmented by the addition of a component $v_\parallel/\Omega_{\rm c\ pol}\ df_0/dr$ representing the first order effects of finite banana width, (2) the passing particle distributions are taken to be continuous with the trapped particles, including the finite banana modification. A similar modification of a bounce-averaged Fokker-Planck code has been undertaken by Westerhof [4]. These modifications account for dominant effects leading to the bootstrap current. The range of validity of this model will be discussed with respect to first principles and code results will be compared with standard neoclassical formulas. The CQL3D code contains terms for quasilinear diffusion due to fast waves, lower hybrid waves, and electron cyclotron waves. For typical experimental conditions, each of these wave modes will be examined as to their effectiveness in producing rf enhanced bootstrap current.

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EFFECTS OF ION DIAMAGNETIC FLOW ON SHOCK FORMATION IN POLOIDALLY ROTATING TOKAMAK PLASMAS*

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When the poloidal ion diamagnetic flow is of the order of the $\mathbf{E} \times \mathbf{B}$ drift velocity, it significantly affects the shock formation in a poloidally rotating tokamak plasma, mainly through gyroviscosity. (Here, $\mathbf{E}$ is the electric field, and $\mathbf{B}$ is the magnetic field.) The poloidal density variation in both linear and shock regimes can be weakened if the poloidal ion diamagnetic flow tends to cancel the poloidal $\mathbf{E} \times \mathbf{B}$ flow. The magnitude of the density variation is not symmetric with respect to the direction of the $\mathbf{E} \times \mathbf{B}$ poloidal rotation. The resonant condition at which strong shock occurs is also modified dramatically by the diamagnetic flow. For some cases, the poloidal density variation inside the bifurcated electric field layer in the L-H transition may not be large enough to significantly modify the plasma viscosity obtained by neglecting the compressibility effects.

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Trapped-Particle Effects In The Nonlinear Evolution Of Magnetic Islands *

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It has been demonstrated within the framework of neoclassical MHD theory [1], that the fluctuating bootstrap current can nonlinearly sustain magnetic islands in tokamaks in situations when the tearing-mode stability index Δ' is negative. In that theory it was assumed that the plasma pressure equilibrates along the perturbed magnetic surfaces, so that it is a function of a generalized poloidal flux, $p = p(\psi)$, where $\psi = -x^2 B_0/2L_s + \tilde{\psi} cos\alpha$. On the other hand, in high temperature plasmas such as modern tokamak experiments, the deviation of particle orbits from the flux surface due to the finite banana width might be sufficient to violate the condition $p = p(\psi)$, leading to poloidal oscillations in the pressure of trapped particles. In a toroidal magnetic field, such oscillations yield an additional contribution to the current closure equation

$$\nabla_{\|} J + < \mathbf{B} \cdot \nabla\tilde{p} \times \nabla(\widetilde{\frac{1}{B^2}}) >= 0$$

where $< \cdots >$ means everaging along the bounce trajectory and $(\widetilde{\cdots})$ corresponds to bounce oscillations of corresponding quantities.

Resonant magnetic perturbations that create the magnetic islands also produce perturbations of the electrostatic potential. In a stationary state the electrostatic potential can be considered to be approximately constant on magnetic surfaces. Because of the finite deviations of the particle orbits from the magnetic surface, the effective $\mathbf{E} \times \mathbf{B}$ drift experienced by the ions will be different from that for electrons. This difference creates a direct mechanism of charge separation, which, via charge neutrality, induces a longitudinal current. This mechanism is physically similar to that considered by Rebut and Hugon[2] for islands whose width is comparable to the ion Larmor radius. The longitudinal current induced by the combination of the above trapped particle effects may substantially modify the island dynamics when the ion banana width is comparable to the island width. These effects are being quantified and their influence on neoclassical MHD tearing modes (in particular the smaller scale, higher mode number ones) will be discussed.

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FINITE BANANA ORBIT EFFECTS IN THE PRESENCE OF MINI-MAGNETIC ISLANDS*

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To address the interaction of trapped ions on magnetic islands, the contribution of collisionless finite banana orbit effects on the parallel (to the magnetic field **B**) current is investigated. In this calculation the width of the magnetic islands and the ion banana orbits are assumed to be small compared with the characteristic equilibrium gradient scale length, a, but comparable to each other, *e.g.*, $w_{isl} \sim \Delta r_T \ll a$. The ion drift kinetic equation is solved near the rational flux surface for a single resonant helicity perturbation of the magnetic field, $\mathbf{B}_1 = \nabla\times(-\psi_1\nabla\zeta) \sim \exp\{im(\theta - \zeta/q_s)\}$. Here, θ is the poloidal angle, ζ the toroidal angle, and $q_s = m/n$ the safety factor on the rational flux surface. Then, using this solution, the parallel current will be calculated in combination with the electron drift kinetic solution previously solved by Hegna and Callen[1], where the electron banana width effects are neglected since the electron poloidal gyro radius is taken to be very small with respect to the magnetic island width.

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Simulations of Interacting Bootstrap-Current-Driven Magnetic Islands*

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The results of one-dimensional simulations of interacting fluctuating neo-classical pressure gradient driven magnetic islands for a tokamak plasma are presented. The dynamics of the magnetic islands are based on model equations that describe the growth and decay of the islands' widths due to the bootstrap current drive and the island interaction.[1] Early simulations of multiple islands located between the q=2 and q=3 rational surfaces have indicated the importance of evolving the pressure profile across the model region. The dynamics of the island half-widths relative to various transport and heating models will be explored to address pressure evolution effects.

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Diverting α-particle Power to Tail Ions in a Reactor†

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There are conditions under which energetic α-particles in a tokamak reactor may amplify certain waves, such as the lower-hybrid wave [1]. There are two very good things that might be done with the wave energy: One, to channel the wave energy into fast electrons traveling in one direction—this accomplishes the current-drive effect. Two, to channel the energy into the tail of the ion distribution—this increases the fusion reactivity.

We assess the utility of these possibilities, paying particular attention to the implications of diverting power to the energetic ions, and analyzing what requirements would be placed, in achieving this effect, on the propagation of the lower-hybrid wave.

It might be noted that the extraction of energy envisioned here is essentially an *in situ* direct conversion method. Fusion products are used not just to heat, but to perform useful work. The advantage over even the direct conversion of this energy to work is that, since it is converted *in situ* and directly to the end use, the inefficiencies associated with intermediate stages, such as generating waves and delivering the wave power to the tokamak, are also avoided, thereby enhancing the current-drive effect when the power is eventually absorbed by electrons or the fusion reactivity if the power is delivered to the ions. Waves traveling in one poloidal direction, in addition to being directed in one toroidal direction, turn out to be the most efficient in tapping the energetic α-particle power.

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RADIAL TRANSPORT AND THE DYNAMICS OF THE TRANSITION TO NEUTRALIZER REGIMES IN GAS-FUELED DIVERTORS

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Increasing the distribution of divertor plate heat loads is a central goal of ongoing boundary physics research in the fusion program. In one scheme, the gas-target divertor, it is proposed that puffing a high density neutral gas will 'extinguish' the hot plasma before it strikes the divertor plates. The viability of this scheme has been demonstrated by basic experiments on PISCES,[(1)] in which a dramatic increase in radial transport accompanied the development of the gas target.

Here, we report on theoretical investigations of radial transport in an SOL plasma with a high neutral density. Previous work[(2)] on ionization-drive drift wave turbulence is extended to regimes where $\gamma_I, \gamma_{cx} > \omega_*$. In contrast to previous results for low neutral density, the particle and heat flux are found to be outward. Nonlinear rate balance is used to estimate fluctuation levels and transport coefficients. These are then used to develop a criterion for access to the gas target (neutralizer) regime.

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MODELING THE ICRF-EDGE INTERACTION IN H-MODES*

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Our understanding of the ICRF-edge plasma interaction has increased greatly in recent years. One important result has been the virtual elimination of ICRF-specific impurities during ICRF heating on JET. It has been shown that impurity release from ICRF antennas is an effect of rf sheaths. An rf-sheath model gives good agreement with JET impurity influx data and suggests a practical prescription for reducing impurities to negligible levels.[1] Another important development, made possible by the reduction in impurities, was the achievement of H-modes induced by ICRF heating alone under conditions in which rf sheaths were expected to be robust (monopole phasing) and to be neglgible (dipole phasing). It was found that the quality, duration and termination mechanism of the H-mode was different in the two cases. In this paper, we describe simulation results and experimental data which provide a possible explanation for the unique properties of the monopole ICRF H-mode. The simulation shows that the rf sheaths near the antenna drive large convective cells,[2] which penetrate the SOL and cause enhanced edge transport. The edge convection is a good candidate to explain the reduction in quality of the the highly-sheared, poloidally uniform H-mode transport barrier, and the resulting flattening of the SOL density and temperature profiles may explain the longer duration and the absence of a radiative collapse for the monopole H-mode. An analysis of JET data shows the existence of phasing-dependent ICRF-enhanced edge transport in agreement with the theoretical model.

The 2D simulation results will be discussed and compared with the available experimental data. This work suggests that ICRF antennas in monopole or FWCD phasing provide another practical means of biasing the edge plasma to control the global confinement, central density and impurity accumulation in H-mode operation.

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Effect of Clumps on the Frequency Spectrum of Trapped Electron Driven Drift Wave Turbulence*

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Experimental measurements of plasma turbulence often predict the spectrum as a function of both the wave number and the frequency S(k,w). Turbulence theories, however, have typically predicted the spectrum only as a function of the wave number S(k) due to the difficulties associated with predicting the frequency spectrum.[1] In addition, recent numerical simulations of dissipative trapped electron driven turbulence have seen large nonlinear frequency shifts which can affect both stability and transport.[2]

A nonlinear theory of the effect of localized density fluctuation elements (clumps) on the frequency spectrum of dissipative trapped electron driven turbulence is presented. A two-point theory for the dissipative trapped electron mode is discussed. In previous theories of clump emission processes,[3] only the imaginary part of the incoherent contribution to the electron dielectric, which corresponds to frequency broadening, has been considered. It is shown, however, that the real part contributes a nonlinear frequency shift. This nonlinear frequency shift can affect both stability and transport by altering the phase between the trapped electron response and the electrostatic potential. An analytic formula for the frequency shift and broadening is obtained.

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THREE-DIMENSIONAL FIELD SOLUTION FOR THE QUIET IMPLICIT PIC METHOD*

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Solution of the time-implicit moment equations for electron and ion species combined with Maxwell's equations is the kernel of the moment-implicit particle method and of the quiet implicit PIC method (a generalized δf method for electromagnetic plasma simulation). Previous implementations have used a variety of direct and iterative approaches for obtaining solutions. These methods have suffered from both excessive computational cost (sometimes negating the advantage of implicit time differencing) and from lack of convergence in some regimes of interest (rendering the method inapplicable). We describe a new formulation of the coupled problem, leading to a symmetric, positive definite system. We also show that this symmetric problem may be efficiently and reliably solved by a conjugate gradient method. A three-dimensional algorithm using a pseudospectral Fourier treatment of the poloidal and toroidal directions, and a finite difference treatement of the radial direction has been constructed. The radially-dependent, poloidal and toroidal averaged operator is used as a preconditioner. Convergence is rapid (typical iteration count of 10 for 10^{-5} convergence). Applications of these methods to two-fluid simulation of MHD instabilities in a tokamak are presented, including results for the $m = 1$ internal kink (sawtooth).

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On the FLR Stabilization of High Poloidal Mode Number External Kinks*

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High poloidal mode number ideal instabilities, localised near the edge of the plasma column and driven by the gradient of the plasma current, are thought [1] to be a serious limitation to operation of long–pulse experiments, such as the Steady State Advanced Tokamak (SSAT/TPX). In particular, the kink (with toroidal mode number $n = 1$), which requires a close–fitting conductive wall for stability, will limit [1] the maximum value of β for the experiment. Since wall stabilization is only effective for an L/R time, defined by the material properties of the conducting shell, this intability becomes of concern for the long–pulse experiments.

It has been known for a long time that many classes of instabilities can have their linear growth rate reduced, and even eliminated, by the so–called finite Larmor radius (FLR) effect. Among them are interchange modes [2] and pressure–driven $m = 1$ modes [3] (here m is the poloidal mode number). This stabilization arises from the breaking of the single–fluid approximation of the plasma response to the perturbation. When the ion and electron responses are decoupled, diamagnetic effects ($\omega_* = (k_\theta c/enB)dp/dr$) arise in the equation governing the linear stability and can bring about stabilization. A derivation in cylindrical geometry leads to the following linear dispersion equation:

$$\frac{d}{dr}\left\{r^3\left[F^2 - 4\pi\rho\omega(\omega-\omega_{*i})\right]\frac{d\tilde{v}_r}{dr}\right\} - r(m^2-1)\left[F^2 - 4\pi\rho\omega(\omega-\omega_{*i})\right]\tilde{v}_r = 0$$

This equation, together with the appropriate boundary conditions (plasma - vacuum) will be solved to determine the efficacy of FLR stabilization. This work is intended to be a preliminary investigation in the simple cylindrical geometry. Extension to a realistic toroidal configuration is planned.

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THE EFFECT OF AN AXIAL CURRENT ON PARTICLE LOSS CONE IN AN AXIALLY SYMMETRIC MIRROR

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Recent research in the Current Drive Experiment-Upgrade (CDX-U), low-aspect-ratio tokamak, has been concentrated on non-inductive current drive experiments for future steady-state tokamaks. To understand the observed current level in these experiments, we first carry out particle orbit studies using a simple mirror configuration with an axial current. Particles are confined by mirroring forces and by conservation of angular momentum. This distorts the loss cones and can result in current generation through preferential losses. The equation of motion for a single particle in this magnetic configuration is solved numerically, and modification to the usual mirror loss-cone is studied. Particles having a preferred azimuthal velocity component tend to be lost at one end or the other. The results of PIC code studies and analysis will be presented and implications on the mechanism for Bootstrap current will be discussed.

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Toroidal Drift Waves with an Equilibrium Velocity Field

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Abstract

We investigated the effect of a *radially* sheared poloidal velocity field on the toroidal drift wave which is well known to escape magnetic shear damping through toroidal coupling between different poloidal harmonics centered on individual rational surfaces. We endeavoured to model our velocity profile according to that observed at the plasma edge during H-mode shots. The resultant wave formed by the interference of different polodal harmonics now *sees* an *antiwell* created by the H-mode type velocity profile in the radial direction (in contrast to a *well* formed by the diamagnetic frequency in the absence of velocity fields). The wave, therefore, convects energy outward and hence undergoes damping! Outgoing wave boundary condition then introduces a negative imaginary contribution to the global eigenvalue - once again confirming the stabilizing role of H-mode type velocity profiles. On the other hand, L-mode type velocity profiles have destabilizing action on toroidal drift waves.

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Anomalous Momentum Transport from Drift Waves

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A sheared slab magnetic field model $\underset{\sim}{B} = B_0[\hat{\underset{\sim}{z}} + (x/L_s)\hat{\underset{\sim}{y}}]$, with inhomogeneous flows in the $\hat{\underset{\sim}{y}}$ and $\hat{\underset{\sim}{z}}$ directions, is used to perform a fully-kinetic stability analysis of the ion temperature gradient (ITG) and dissipative trapped electron (DTE) modes. The concomitant quasilinear stress components that couple to the local perpendicular (y-component) and parallel (z-component) momentum transport are also calculated and the anomalous perpendicular and parallel viscous stresses obtained. A breakdown of the ITG-induced perpendicular viscous stress is generally observed at moderate values of the sheared perpendicular flow [1]. The ITG-induced parallel viscous stress is generally larger and strongly dependent on the sheared flows. The DTE-induced perpendicular viscous stress may sometimes be negative, tending to cancel the ITG contributions while the DTE-induced parallel viscous stress is generally small. The effect of the perpendicular stress component in the momentum balance equations is generally small while the parallel stress component can dominate the usual neoclassical viscous stress terms [2]. The dominant contribution to parellel viscous stress by the ITG mode suggests that bulk plasma toroidal momentum confinement, like energy confinement, is governed by an anomalous ion loss mechanism. Furthermore, the large anomalous effect suggests that the neoclassical explanation of poloidal flows in tokamaks may be incorrect. The present results are in general agreement with existing experimental observations on momentum transport in tokamaks [3].

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RESONANCE PARALLEL VISCOSITY IN THE BANANA REGIME IN POLOIDALLY ROTATING TOKAMAK PLASMAS*

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Parallel viscosity in the banana regime in a poloidally $(\mathbf{E}\times\mathbf{B})$ rotating tokamak plasma is calculated to include the effects of orbit squeezing and to allow the poloidal Mach number, M_p, to have a value of order unity. Here, $\mathbf{E}$ is the electric field and $\mathbf{B}$ is the magnetic field. The effects of orbit squeezing not only modify the size of the particle orbit, but also change the fraction of the poloidally trapped particles. The resonance between the particle parallel (to $\mathbf{B}$) speed, u, and the poloidal component of the $\mathbf{E}\times\mathbf{B}$ velocity can only occur for those particles with energy $(v/v_t)^2 > M_p^2$. Thus, the resonance parallel plasma viscosity decreases exponentially with M_p^2 when $M_p \geq 1$, as originally noted in [K. C. Shaing, E. C. Crume, Jr., and W. A. Houlberg, Phys. Fluids B **2**, 1492 (1990)]. Here, v_t is the thermal speed and v is the particle speed.

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Reconstruction of Ideal MHD Equilibria with Anisotropic Pressure and Azimuthal Mass Flow from Measurements*

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As shown by L. Lao and co-workers[1], tokamak equilibria can be reconstructed by seeking a least-squares "best-fit" between experimental measurements and computed free-boundary equilibria. This technique has become a standard data analysis tool for tokamaks enabling the detailed comparison between predicted and observed MHD stability behavior. In this poster, we report progress to extend this numerical data analysis technique to axisymmetric plasmas with anisotropic pressure and toroidal mass flow. A new computer code has been written which iteratively solves the equilibrium equation

$$r^2 \nabla \cdot \left(\frac{1}{r^2} \nabla \psi\right) = - r\mu_0 J_\varphi$$

where the toroidal current J_φ is expressed as[2]

$$J_\varphi = r p_\parallel' + \frac{B_\varphi}{\mu_0}\left[(1-\alpha)\, rB_\varphi\right]' + r\alpha\left(\frac{B^2}{2\mu_0}\right)' - \frac{r}{\mu_0}\nabla \cdot \left(\frac{\alpha}{r^2}\nabla\psi\right) - \rho\Omega^2 r^2 r'$$

The variables B_φ, ρ, $p_\parallel$, $p_\perp$, and $\alpha \equiv \mu_0(p_\parallel - p_\perp)/B^2$ are related to the solution, ψ, and the five flux functions: the toroidal flow, Ω, the normalized parallel pressure, $S_\parallel = p_{//}B^2/\rho^3$, the normalized perpendicular pressure, $S_\perp = p_\perp/\rho B$, the adjusted toroidal flux, $I = (1-\alpha)\, rB_\varphi$, and the generalized Bernoulli function, $H = 3p_{//}/2\rho + p_\perp/\rho - r^2\Omega^2/2$. After each iteration of the equilibrium solution, the coefficients to polynomial expansions of the flux functions are relaxed towards a solution which minimizes the mean square error between a variety of measurements (such as poloidal field, perpendicular pressure, and density) and the equivalent localized values calculated in terms of the current iteration. A somewhat complex linearization procedure is needed to related the unknown coefficients of the flux functions to the measurable quantities.

Initial tokamak equilibria will be presented illustrating the differences between reconstructions which assume isotropic pressure without flow and those which assume anisotropic pressure with toroidal flow. Representative parameters are taken from the TFTR device when operated at high $\varepsilon\beta_p$ with NBI. This reconstruction technique can also be applied to axisymmetric equilibria of planetary magnetospheres (when $I = 0$) using data collected by satellite fly-bys. A discussion of the differences between the new code and the calculations of Caudal[3] (who considered isotropic pressure with toroidal flow in Jupiter) and Cheng[4] (who considered anisotropic pressure without flow for earth) will be presented.

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SHEAR FLOW GENERATION BY REYNOLDS STRESS AND SUPPRESSION OF RESISTIVE g MODES

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We have investigated suppression of the resistive g mode turbulence by background shear flow produced by the external source and by the fluctuation-induced Reynolds stress. For that purpose, we used the model consisting of the equations describing the electrostatic potential $\phi(\equiv \phi_0 + \tilde{\phi})$ and the pressure fluctuation p of the resistive g mode:

$$\partial_t \nabla_\perp^2 \phi + [\phi, \nabla_\perp^2 \phi] = -\sigma \nabla_\parallel^2 \phi - g\partial_y p + \mu \nabla_\perp^4 \phi$$

$$\partial_t p + [\phi, p] = -\kappa \partial_y \phi + \chi \nabla_\perp^2 p$$

and the equation for the back ground poloidal flow $v_E \equiv d\phi_0/dx$:

$$\partial_t v_E + \nu(v_E - V) = -\partial_x \langle \tilde{v}_x \tilde{v}_y \rangle.$$

Here V denotes external flow, ν the relaxation rate, and $-\langle \tilde{v}_x \tilde{v}_y \rangle$ the Reynolds stress caused by the potential fluctuations $\tilde{v} = \hat{z} \times \nabla \tilde{\phi}$. The neoclassical theory gives certain expressions for V and ν, which we have estimated in the resistive g units.

We have done the single-helicity nonlinear simulations using the model equations in the sheared slab configuration. We find that, in the nonlinear turbulent regime, significant suppression of the turbulent transport is realized only when the shear flow v_E' exceeds that which makes the fastest-growing linear modes marginally stable. With the shear flow which decreases the fastest linear growth rates by about a half, the turbulent transport in the saturated state is about the same as in the case of no shear flow. As seen from the equation for the background flow v_E, the relative efficiency of the external flow and the Reynolds stress for producing shear flow depends on the parameter ν. For large ν, the external flow is a dominant contribution to the total background poloidal shear flow although its strength predicted by the neoclassical theory is not enough to suppress the turbulence significantly. On the other hand, for small ν, we observe that, as the fluctuations grows, the Reynolds stress becomes large and suddenly at some critical point in time shear flow much larger than the external one is generated and leads to the significant reduction of the turbulent transport just like that of the L-H transition in tokamak experiments. It is remarkable that the Reynolds stress due to the resistive g mode fluctuations works not as a conventional viscosity term weakening the shear flow but as a negative viscosity term enhancing it. We show from the quasilinear analysis of the fluctuations that the potential eigenfunction of the resistive g mode in the shear flow can really yield the Reynolds stress enhancing shear. In that case, the tilting angle of the vortex with respect to the direction of the background flow is opposite to that in the case of the shear-weakening vortex, which is confirmed in the simulations. We have also developed the weakly nonlinear (or bifurcation) theory taking account of the shear flow generation due to the Reynolds stress for the resistive g modes.

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A TRANSMISSION/ESCAPE PROBABILITIES MODEL FOR NEUTRAL PARTICLE TRANSPORT IN THE OUTER REGIONS OF A DIVERTED TOKAMAK

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A new computational model for neutral particle transport in the outer regions--the edge plasma, the SOL, the divertor channels, and the plenum regions--of a diverted tokamak is proposed. The concept is to represent the outer regions of a diverted tokamak with a relatively small number of geometrically complex regions and to do a balance on the fluxes that cross the bounding surfaces. The uncollided neutral flux that is transmitted from one surface to another is calculated with integral transport theory. The secondary source in the intervening region is then found by subtraction, and the collided neutral fluxes through the bounding surfaces are calculated by repeated application of first-flight integral transport theory. With a few plausible assumptions, the resulting transmission and escape probabilities depend only on geometry and mean free path(mfp), so that complex geometries can be represented in precomputed coefficients that depend only on the mfp of the region, thereby eliminating the computational penalty of geometric complexity. Such a model should be able to attain greater accuracy than the simple first-flight integral transport and diffusion models, at a comparable computational time.

The formulation of the flux balance, the calculation of the transmission and escape probabilities, the treatment of regions bounded by a material surface, and the treatment of impurity atoms will be discussed. Transmission and escape probabilities will be presented for regions bounded by straight lines and arcs of circles. The limiting assumption of uniform plasma properties within a geometric region, which places a lower limit on the number of regions required, will be discussed.

Nonlinear Evolution of Alpha-Particle-Driven Alfvén Turbulence and Associated Alpha Transport

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A nonlinear model[1] of alpha-particle-driven Alfvén turbulence was proposed previously. The model describes the coupled evolution of the alpha density profile $n_\alpha(r,t)$ and turbulence spectrum $|\tilde{\phi}|^2_{\bar{k}}(t)$ through the following equations:

$$\frac{\partial}{\partial t}n^\alpha(r,t) + \frac{\partial}{\partial r}\Gamma^\alpha(r,t) = S^f(r,t)$$
$$\frac{\partial}{\partial t}|\tilde{\phi}|^2_{\bar{k}}(t) = 2(\gamma^l_\alpha + \gamma^l_e + \gamma^{nl}_i)|\tilde{\phi}|^2_{\bar{k}}(t)$$

Here, $\Gamma^\alpha(r,t)$ is the quasi-linear alpha particle flux, $S^f(r,t)$ is the alpha particle source, γ^l_α is the alpha growth rate, γ^l_e is the electron Landau damping rate, and γ^{nl}_i is the bulk ion Compton scattering rate. We have solved these equations numerically. The results show that the saturation is achieved by ion-Compton-scattering induced nonlinear coupling between the stable ($\gamma_\alpha < \gamma_e$) and unstable ($\gamma_\alpha > \gamma_e$) part of the spectrum. Due to the non-local nature of this process, the saturated spectrum consists of two well separated peaks (see Fig.), one in the unstable and one in the stable region. The former determines the energy input from the alphas, while the latter determines the energy dissipation to the electrons. The imbalance between the energy input and energy dissipation leads to quasi-periodic oscillations of the total fluctuation energy. Our numerical results show large alpha particle transport only when the alpha growth rate is strong in comparison with the ion Compton scattering rate. This condition depends on the bulk plasma and alpha density scale lengths and β_α.

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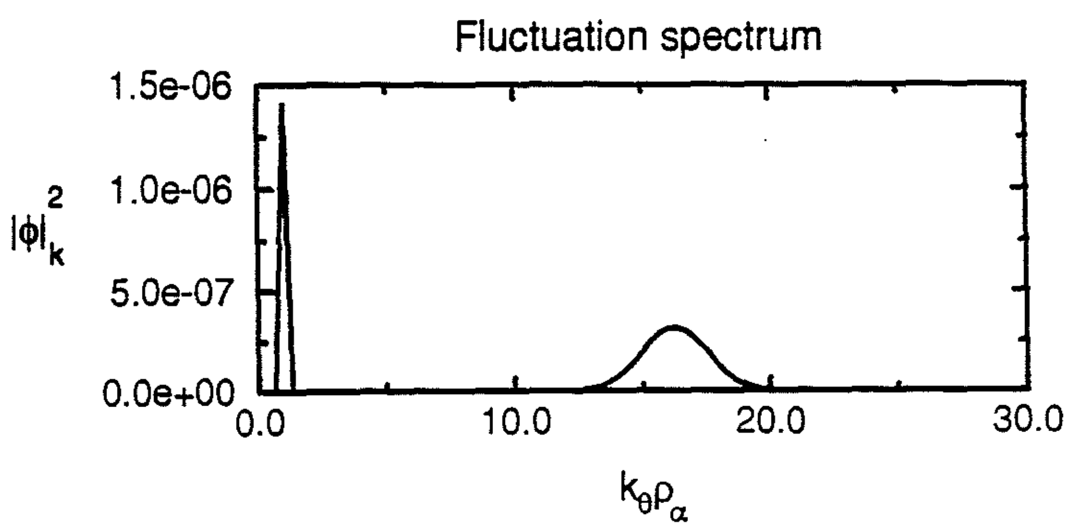

Ultra High β Transport and Stability

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The stability and transport properties of ultra high β tokamaks, $\beta \gg \epsilon/q^2$, are investigated. This work uses the analytic equilibria developed in the paper by Cowley et. al. [Phys. Fluids B, **3**, 2069(1991)]. Recent papers show that these equilibria are stable to localised MHD modes and that neoclassical transport is reduced at high β. Five equilibrium properties suggest that anomalous transport may also be reduced at high β. These are: (i) reduced volume in the boundary layer and therefore reduced trapped particle fraction; (ii) strong average good curvature stabilizing all flute like instabilities; (iii) short connection length in the bad curvature region making all parallel wavelengths large; (iv) strong shear in the bad curvature region; and (v) minimum B producing "drift reversal." Calculations demonstrating the benefits of these properties will be presented. Some discussion of Alpha particle issues at high β will be given.

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A STUDY OF THE GUIDING CENTER APPROXIMATION

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A Hamiltonian treatment for the motion of a charged particle in a toroidal magnetic field is given. Assuming the plasma equilibrium, Boozer coordinates are used. The Hamiltonian of the exact trajectory is given in the guiding center coordinates. The higher order corrections to the standard drift Hamiltonian are derived. It is shown that the exact Hamiltonian depends on both the field strength and the shape of the magnetic surfaces (the metric of Boozer coordinates) while the standard drift Hamiltonian depends only on the field strength. The first order correction to the standard drift Hamiltonian, in gyroradius to system size, depends in a generic way on the shape of the magnetic surface, as does the exact Hamiltonian. Numerical calculations are done to compare the trajectories of the exact Hamiltonian, the standard drift Hamiltonian and the higher order drift Hamiltonian for a quasihelical symmetric vacuum field. The numerical results show that the difference in phase space structure between the exact and standard drift Hamiltonian can be predicted by the drift Hamiltonian with the first order corrections.

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Plasma Transport in Mixed Magnetic Topologies*

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A simple paradigmatic model [1] is introduced to illustrate some features concerning anomalous transport associated with magnetic turbulence. A steady-state magnetic topology is considered that has two distinct regions of confinement, where spatially separated regions of magnetic stochasticity are imbedded in a plasma volume. Correspondingly, where the magnetic stochasticity is present the associated magnetic diffusion of field-lines introduces a plasma transport mechanism in addition to those already present in the plasma. It is shown that the "global" plasma transport coefficients deviate significantly from those describing completely stochastic magnetic fields. In particular, it is possible to have the electron heat diffusivity exceed a runaway electron diffusion coefficient, despite the existence of widespread magnetic stochasticity. A slight modification of this model can also account for the effects of magnetic islands on the plasma transport [2,3]. Comparing the ratios of transport coefficients is not sufficient to distinguish between electrostatic or electromagnetic models of anomalous plasma transport.

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Radiative Divertor Simulations*

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The UEDGE fluid model edge-plasma code is used to study methods for reducing the heat load on divertor plates by radiating some of the power before it reaches the plates. Radiation can be enhanced by hydrogenic gas puffing or by injection of low-Z impurities near the plates. Neutral hydrogen is modeled as a two-species fluid; one species represents Franck-Condon neutrals generated at the plates by molecular breakup, and another species represents energetic neutrals due to charge-exchange processes in the plasma. Rate parameters for ionization, recombination and charge-exchange processes are obtained from the ADPAK[1] package. Non-equilibrium coronal radiation from impurities is parameterized in terms of the local electron temperature, impurity lifetime due to convection, and local neutral hydrogen density. The impurity concentration is specified as input. The electron temperature and radiation losses are calculated self-consistently in the UEDGE model.

Simulations of high-power radiative divertor experiments in DIII-D[2] show a factor of two reduction in divertor heat load with a spatially uniform nitrogen impurity concentration of less than one percent. Deviations from coronal equilibrium occur near the divertor plates where the lifetime of the impurities is reduced by convective flow to the plate and charge exchange on neutral hydrogen. At low divertor temperatures a substantial fraction of the power flowing toward the divertor plates is also radiated due to hydrogen recycling.

UEDGE simulations of the proposed TPX device determine the impurity concentration that reduces the peak heat flux and electron temperature at the divertor plate to acceptable values. Hydrogen gas puffing enhances charge-exchange losses to the divertor walls and reduces the ion heat flow to the divertor plates.

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THE NEUMANN PROBLEM IN TOROIDAL DOMAINS SOLVED BY AN INTEGRAL EQUATION TECHNIQUE FOR THE SURFACE CURRENT

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The 3D MHD free boundary equilibrium NEMEC code [1] combines the fixed boundary VMEC code [2] with the vacuum NESTOR code [3,4]. In NESTOR a Neumann problem is solved for a single valued potential Φ by an integral equation technique satisfying the condition $\vec{B}_V \cdot \vec{n} \equiv \left(\vec{B}_0 + \nabla\Phi\right) \cdot \vec{n} = 0$ on the plasma-vacuum boundary ($\vec{B}_0$ = field produced by external currents and the total toroidal plasma current I_t, $\vec{n}$ = exterior normal to the boundary). The only quantity required for the free boundary equilibrium computation is the value of $B_V^2/2$ at the boundary.

Here, an equivalent method for computing the vacuum field $\vec{B}_V$ is considered which is particularly suited for the case $I_t \neq 0$ and makes use of the fact that this field can be generated by the external current $\vec{j}_{ext}$ and by a surface current $\vec{j}$ on the plasma vacuum boundary satisfying the integral equation

$$\vec{j}(\vec{x}) - \frac{1}{2\pi}\int\limits_{\partial R} df'\vec{n} \times \left(\nabla G(\vec{x},\vec{x}') \times \vec{j}(\vec{x}')\right) = \frac{1}{2\pi}\int\limits_{\partial C} df'\vec{n} \times \left(\nabla G(\vec{x},\vec{x}') \times \vec{j}_{ext}(\vec{x}')\right),$$

where ∂R, ∂C are the plasma and coil boundaries, resp. and $G(\vec{x},\vec{x}') = 1/|\vec{x} - \vec{x}'|$ is the Green's function. The divergence-free surface current $\vec{j}$ can be expressed by a potential $\Psi : \vec{j} = \vec{n} \times \nabla\Psi$. For stellarator symmetry the general ansatz for $\Psi(u,v)$ is given by

$$\Psi(u,v) = \sum_{m=0,n=-N}^{M,N} \hat{\Psi}_{mn} \sin 2\pi(mu + nv) - I_p v + I_t u \ ,$$

where u, v are angle-like variables parametrizing the toroidal domain and I_p ,I_t are the net poloidal and toroidal surface currents, resp.. The currents I_p, I_t are determined by the matching conditions of plasma and vacuum field at the boundary: the poloidal (toroidal) current is given by the toroidally (poloidally) closed integral $I_p = \int \vec{B}_P \cdot \vec{ds}$, ($I_t = \int \vec{B}_P \cdot \vec{ds}$) over the plasma magnetic field at the boundary. The required value of ${B_V}^2$ on the boundary is given by ${B_V}^2 = j^2$. The difficulty inherent to the Green's function method is the numerical integration of the singular Green's function. This is solved by regularizing the kernel: an analytically integrable function with the same singularity is subtracted and its integral is added to the integral equation [3].

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Parallel Flow Gradient Driven Instability*

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Model equations have been studied which are appropriate to the plasma edge and which describe a mode driven by the perpendicular gradient of the parallel velocity ($V'_{||eq}$). This mode can be stabilized by parallel sound waves and by diamagnetic effects. For this reason, large velocity gradients are required for the instability to be operative. In this study we have used $V'_{||eq} \leq 2.65 \times 10^6$ sec^{-1}. We have investigated the nonlinear properties of this instability using single helicity calculations. As reported earlier[1] poloidal flow profile modification is well reproduced by a quasilinear model. In steady state, fluctuation levels of ≤10% are found. The levels decrease as $V'_{||eq}$ does. Diamagnetic effects reduce the saturated levels with the reduction larger for smaller $V'_{||eq}$. Linearly, the peak in the mode is shifted from the rational surface. At small drive, the nonlinear fluctuations have the same radial width as the linear mode and have a simple radial structure. For large drives, the nonlinear fluctuations are extended over ~10% of a plasma radius and have a more complicated structure. Additional linear and nonlinear studies have been made and will be reported.

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THE 1993 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

RADIAL DIFFUSION OF A MINORITY SPECIES IN A TOKAMAK DUE TO ICRH

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We study the transport of a minority species in a scenario where minority ions in a tokamak are heated by fast Alfvén waves having a resonance layer in a tokamak. We do not assume the minority distribution function to be a Maxwellian at leading order, as transport theory generally assumes, but adopt a more realistic model where the strong anisotropy of the distribution function is accounted for. This anisotropy has been observed in experiments [1] and is predicted by numerical calculations based on Fokker-Planck equation with quasilinear diffusion [2]. By adopting a different ordering from that used in previous work on transport due to waves [3] and taking moments of the kinetic equation which includes the RF driving term, we calculate the fluxes of the resonant minority species accounting for collisions of minority with bulk electrons and ion species. Finally we make comparisons of fluxes of RF-heated minority with standard neoclassical predictions (no RF source present) showing the enhancement in transport introduced by the presence of both a strongly anisotropic distribution function and an RF source.

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A Comparison of the Two-Fluid $m = 1$ Stability Criterion to Sawtooth Behavior in TFTR*

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Abstract

An important problem in the theory of internal disruptions in tokamaks is to determine the stability conditions for sawtooth oscillations. A qualitatively reasonable stability criterion for the collisionless $m = 1$ mode, which may explain the observed stable, oscillation-free phase, arises due to ω_*-effects. Recent progress in experimental measurements of tokamak $q-$profiles allows a quantitative comparison of this criterion with experimental data. A reasonable account of the ω_* modification of both collisionless and ideal $m = 1$ modes is given by the (compressible) two-fluid MHD dispersion relation, which is used here for simplicity. The influence of hot particles is not taken into account at the present stage. Many TFTR discharges are analyzed, using magnetic field measurements based on the Motional Stark Effect diagnostic and pressure and plasma density profiles provided by the TRANSP code. It is found that the ω_*-effects seem to give the main contribution to the stabilization of the $m = 1$ reconnection mode and may explain the stabilization of sawteeth in discharges with peaked pressure profiles, where ideal MHD theory is in clear contradiction with experiments.

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Edge Plasma Issues in Divertor Design Illuminated by DIII–D Results

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The effort to develop divertor solutions of the radiative or gas target type for next generation machines is bringing to light many edge plasma physics issues. The use of higher Z radiators in the SOL and divertor requires development of non-coronal equilibrium radiation models for incorporation in fluid codes. Fluid and Monte-Carlo codes need to be upgraded to handle 2-D multi-series impurity transport. Impurity transport along the field lines is a competition between friction from fuel flow (toward the plate) and the thermal force (away from the plate). The experimental basis for and the theoretical validity of thermal force terms need to be established. Experimental measurements can be expected to be decisive on the regime of the fuel flow: conduction limited, sheath limited, or flux limited. If the collisionless sheath or flux limited regimes apply, we need to consider the non-Maxwellian aspects of electron heat flow. The sheath condition, which is influential in these collisionless regimes, is known to be strongly affected by collisional effects with grazing incidence field lines in high recycling and gas target divertors. Non-Maxwellian ion features in the SOL also need to be addressed. Measurements show $T_i \gg T_e$ in the SOL. The high values of ∇T_i just inside the separatrix of H– and VH–mode plasmas mean that a substantial and energetic ion population spills out into the SOL on loss orbits. Ion and electron heat flows are weakly coupled, giving rise to two radial scales in the SOL profiles and in the heat flux to the divertor plate. The role of $E \times B$ drifts and parallel currents in the SOL has also been shown by measurements and code simulations to have large effects. These issues and others are central to designing the divertors in next generation tokamaks.

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MHD Stability Studies of TFTR Plasmas

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Supershot plasmas in TFTR are beset by MHD instabilities which demonstratively spoil their confinement properties. This phenomenon is variously referred to as 'beta-saturation' or 'beta-collapse', depending on the severity of the confinement degradation. In view of their relatively slow growth rates, these instabilities have long been assumed to be purely resistive in character. Here, we have studied both the resistive and ideal MHD stability properties of equilibrium profiles derived from TRANSP analysis of the experimental data. The very steep pressure gradients in the interior, which are a characteristic feature of supershot plasmas, are such that small toroidal mode number ballooning and 'infernal' modes can be excited. These ideal, pressure driven modes can impose a severe limitation on the maximum attainable β. When the finite plasma conductivity is taken into account resistive modes appear which have the effect of blurring marginal points and substantially extending the range of parameters over which instabilities can be excited.

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A Fast, Highly-Accurate MHD Equilibrium Solver

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Experience in recent years has shown that in order to determine MHD stability boundaries in tokamak plasmas reliably require highly accurate plasma equilibria. To attain numerical convergence of many types of MHD modes requires equilibria with minimum grid sizes of 800 by 800 when using second order differences. This is particularly crucial for slowly growing modes and modes that are highly localized. Examples are restitive modes and external kink modes. A consequence of this accuracy requirement is that the equilibrium computation is the main bottle-neck for many types of stability applications. This is especially true for parameter scans and optimization. Progress will be reported on a multigrid flux-coordinate based equilibrium code we are developing. The code will eventually include tensor pressure and plasma flow. In addition to computations on large grids, initial results indicate that for applications requiring less resolution, such as equilibrium solver in a transport code, the multigrid method may be competitive with moment based equilibrium computations.

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THEORY OF MODULATIONAL INTERACTION OF TRAPPED ION CONVECTIVE CELLS AND DRIFT WAVE TURBULENCE

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Theoretical and computational studies of the modulational interaction between trapped ion convective cells and short wavelength drift wave turbulence are discussed. These studies are motivated by the fact that cells and drift waves are expected to coexist in tokamaks so that:

a.) cells strain and modulate drift waves

b.) drift waves 'ride on' a background of cells.

The results of our investigation indicate that:

i.) (nonlinear) parametric growth rates of trapped ion convective cells can exceed linear predictions (for drift wave levels at the mixing length limit);

ii.) a set of coupled envelope equations, akin to the Zakharov equations from Langmuir turbulence, can be derived and used to predict the formation of a dipole pair of convective cells trapped by the drift wave envelope. This dipole pair is strongly anisotropic, due to the structure of the drift wave Reynolds stress which drives the cell flow. Numerical solutions of the envelope equations are in good agreement with theoretical predictions, and indicate the persistence of the structure in time;

iii.) strong modulation and trapping of drift waves with $k_{\perp}\rho > 1$ occurs;

Extensions to magnetically sheared systems and the broader implications of this work as a paradigm for the dynamics of persistent structures in shearing flows will be discussed.

ALTERNATE FUSION - CONTINUOUS INERTIAL CONFINEMENT*

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We argue that alternate approaches to large tokamak confinement are appropriate for fusion applications *if*: 1) They do not require magnetic confinement of a much higher quality than demonstrated in tokamaks; 2) Their physics basis may be succinctly stated and experimentally tested; 3) They offer near-term applications to important technical problems; and 4) Their cost to proof-of-principle is low enough to be consistent with current budget realities. An approach satisfying all of these criteria is presented.

Fusion systems based on continuous inertial confinement are described. In these approaches, the inertia of a nonequilibrium plasma is used to produce local concentrations of plasma density in space and/or time. One implementation (inertial electrostatic confinement) which has been investigated both experimentally and theoretically uses a system of electrostatic grids to accelerate plasma ions toward a spherical focus. This system produced a steady 2×10^{10} D-T neutrons/second with an overall fusion gain of 10^{-5} in a sphere of about 9 cm radius.[1] Such compact systems have a variety of assaying applications involving, for example, neutron activation of low-Z nuclei.

Recent theoretical developments[2] show how to raise the fusion gain to order unity or greater by replacing the internal grids by a combination of applied magnetic and electrostatic fields. In these approaches, useful thermonuclear conditions may be produced in a system as small as a few mm radius! Confinement is that of a nonneutralized plasma. A pure electron plasma with a radial beam velocity distribution is absolutely confined (with finite barrier height) by an applied Penning trap field. Spherical convergence of the confined electrons forms a deep virtual cathode near $r = 0$, in which thermonuclear ions are absolutely confined at useful densities.

We have examined the equilibrium, stability, and classical relaxation of such systems, and obtained many positive physics results. Equilibria exist for both pure electron and partially charge-neutralized systems with arbitrarily high core-plasma densities. The electrostatic stability of such systems is given by the zeros of a quadratic form, indicating a stability margin of an order of magnitude in mean plasma density, independent of convergence. Classical relaxation of a sufficiently cold system maintains an extremely low perpendicular (to r) temperature *via* equipartition with a cool radial temperature maintained by particle throughput.

These theoretical results allow the design of high-power density, high-fusion gain, extremely compact spherical fusion systems. A sketch of immediate and long-term experimental opportunities is given.

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* Work supported by US DOE

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Abstract for the 1993 Sherwood Conference

Calculation of an Effective Fast Electron Diffusion Coefficient from 2-D Hard X-ray Images from PBX-M

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The degree of fast electron localization and their transport properties are important for tokamak current profile control schemes, for example as required by TPX. The hard x-ray camera on PBX-M is a unique diagnostic producing two-dimensional, time resolved tangential images of fast electron bremsstrahlung. The rich information contained in the hard x-ray images invites an attempt to compute an effective fast electron diffusion constant for this process.

Our approach is to assume an extremely radially narrow lower hybrid power absorption profile. A transport model based on Rax and Moreau[1] that includes frictional slowing down, pitch angle scattering, electric field effects, lower hybrid effects, and diffusion with an effective diffusion constant as a free parameter, is used to compute a theoretical fast electron current density profile. This profile is compared with an experimental profile which is extracted from the hard x-ray images using a code which models the 2-D images using an assumed radial profile and velocity distribution in the form of a bi-Maxwellian. The model radial profile is recomputed using different diffusion constants until a good match is found, thereby deriving an effective diffusion constant for that image. This presentation will introduce the diagnostic, its data, theoretical models, and results from comparison with theory and experiment.

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Developments in the Gyrofluid Approach to Tokamak Turbulence Simulations

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Fluid equations have long been used to gain insight into plasma instabilities and turbulence. Recent work has aimed to extend the range of validity of fluid equations to a more collisionless regime typical of tokamaks, by developing fluid models of important kinetic and FLR effects. In combination with efficient field-line coordinate systems, and the tremendous advances in massively parallel computing, this offers a possible approach to the ultimate goal of successfully simulating tokamak turbulence and transport.

The basic fluid model of Landau damping[1] has been extended to a fuller set of "gyrofluid" equations[2], derived by taking moments of the gyrokinetic equation, thus expressing fundamental nonlinear conservation laws (for the guiding center density, momentum, parallel energy, magnetic moment, etc.) which the turbulence must satisfy, including a systematic treatment of linear and nonlinear FLR effects using robust Padé-like models. In particular, a new dissipative effect is found in the FLR-modified nonlinear ExB drift which is comparable in magnitude to the usual "polarization drift nonlinearity" and provides damping at high $k_\perp \rho$. The gyrofluid equations have also been extended to include toroidal drift resonances[3] neccessary for the toroidal ITG mode. Further extension to trapped ion effects important at longer wavelengths is still under way. In our simulations to date we have focussed on ITG turbulence as a paradigm, though the ultimate gyrofluid simulation code should eventually include a number of important effects (which have been studied by various researchers) such as collisions, electron dynamics (including trapped electrons), multiple ion species, radial variation of ω_*, and fully electromagnetic perturbations.

We use a field-line coordinate system[4] which allows high resolution runs in the minimum-neccesary simulation volume: a twisting flux tube which takes advantage of the short perpendicular correlation lengths while allowing for long parallel correlation lengths. (Ultimately, convergence must be tested by varying the simulation box size.) With the right parallel boundary conditions, this is equivalent to the ballooning representation, but it clarifies how to quickly evaluate the $\mathbf{E} \times \mathbf{B}$ nonlinearity with FFT's by noting that the nonlinearity is invariant under the transformation to field-line coordinates[4]. These coordinates also provide periodic radial boundary conditions which allow the $(m = 0,\ n = 0)$ components of fluctuations (including self-generated poloidal flows) to vary self consistently while maintaining fixed average background gradients.

We have implemented the gyrofluid equations for toroidal ITG turbulence in a nonlinear 3-D code. We find that with the proper adiabatic electron response, $\tilde{n}_e/n_0 = e(\Phi - \langle\Phi\rangle)/T_e$, where $\langle\ \rangle$ is a flux surface averaged, a sheared poloidal rotation is nonlinearly generated which in turn damps the unstable modes. This indicates the importance of finding all of the relevant mechanisms involved in generating and damping sheared flows. Self-generated sheared flows have been seen in edge turbulence simulations and may play an important role in the H-mode[5,6,7], but have been missed in previous ITG simulations because of limitations in electron response or boundary conditions.

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Alpha-Particle-Driven Nonideal Toroidal Alfvén Eigenmodes*

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The excitation of nonideal Toroidal Alfvén Eigenmodes (TAE) by high energy alpha particles is examined. Specifically, the kinetic α-particle response (including finite banana width effects) is retained directly in the linear mode coupling equations, and represents a driving source proportional to the spatial gradient of the zero order α-particle distribution function. The model is an extension of the recently studied high-m, large aspect ratio, asymptotic boundary layer theory of the nonideal TAE[1], and provides a self-consistent method for the determination of the instability threshold and growth rate of the excited TAE. Numerical results are presented for the simple case of slowly varying density and shear, as well as for specific machine profiles.

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The Radial Electric Field Near a Separatrix in Diverted Tokamaks

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The electric field just inside the separatrix is known to play an important role in the suppression of edge turbulence which leads to the L–H transition. It is also known that divertor biasing affects the L–H transition. It is therefore interesting to know what physics determines the electric field near a separatrix. Although the radial electric field must vary smoothly across a separatrix, it is apparently determined by quite different mechanisms inside and outside. Outside the separatrix, the parallel Ohm's law and charge conservation, along with boundary conditions at the divertor plates, determine the potential and the electric field. Inside the separatrix, the radial electric field is not determined by those equations, since the boundary conditions on the potential only require periodicity. It must be determined by the radial component of the ion momentum equation.

A unified approach is developed for determining the radial electric field both inside and outside the separatrix, in which appropriate components of the momentum equations are used. The required equations are formulated in a form which should be convenient for solution by an edge transport code. Cancellations between the gyroviscous stress terms and certain convective inertia terms are pointed out for the parallel and toroidal momentum equations. The turbulent contributions to these momentum equations are derived in a general form, starting from a kinetic equation which includes turbulent scattering. It is shown that the turbulence term in the parallel momentum equation can be neglected, while that in the toroidal momentum equation is important. The radial current is shown to be related to polarization current and non-intrinsically-ambipolar turbulent radial diffusion.

The equations are shown to reproduce the two limits mentioned above, well inside and well outside the separatrix. It is shown that a radial current is necessary near the separatrix, in order to allow a smooth continuation of toroidal flow and radial electric field across the separatrix. This radial current may allow the radial electric field just inside the separatrix to be altered by divertor biasing, which can therefore affect the L–H transition.

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Edge Physics Satellite Meeting
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Numerical Models for the Edge Plasma

Bastiaan Braams for the
Divertor and Edge Plasma Theory Working Group

The physics of the edge plasma involves closely coupled diverse processes: plasma transport along and across the magnetic field, neutral gas dynamics, atomic collision processes (ionization, recombination, radiation, charge exchange) and plasma-surface interaction processes (sputtering, sublimation, redeposition). This presentation will provide an overview of the numerical tools now used for edge plasma modelling and will discuss opportunities for new contributions of computational plasma theory. In the area of basic plasma physics an important open task is to study multi-species parallel transport along the magnetic field in a regime in which the mean free path is comparable to the gradient scale length, to delineate the validity of classical parallel transport theory and to test or to calibrate various "extended" fluid theories. The problem can be approached either on the basis of the Fokker-Planck equation or with use of collisional particle simulation. Another open task in edge plasma modelling is to extend present plasma codes to handle properly the transition from an ionized plasma to a neutral gas, or to develop a new code that is valid in both regimes. Very little has been done to-date in accounting for three-dimensional magnetic field effects (due to field errors, deliberate perturbations or internal modes) on transport in the edge plasma. Finally, we only mention the largest outstanding issue, which is to bring turbulence modelling to bear on the edge plasma.

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Turbulence in Tokamak Scrape-Off Layers*

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Turbulence plays a beneficial role in a tokamak scrape-off layer (SOL) by spreading the heat load on the plasma-facing components. As a site for turbulence in a tokamak, the SOL is unique because of its open-ended geometry, the extreme disparity between the equilbrium radial and poloidal (or axial) scale lengths, the high local concentration of neutrals and impurities, and its relatively high collisionality. Theoretical studies of SOL turbulence are in their infancy. This paper surveys this emerging field, concentrating on modes which tap into the properties cited above. These include modes driven by plasma rotation relative to conducting end walls and/or axially sheared rotation within the plasma, current-driven interchange modes destabilized by incomplete line tying, Kelvin-Helmholtz instabilities driven by a radial magnetic sheath, and ionization and radiation-driven modes. We review the physical origin of each, discuss conditions under which each is likely to be important, and comment on the status of and needs for the theoretical description of these modes. We discuss the relative importance in the SOL of modes familiar from studies of other parts of the tokamak, such as ion-temperature-gradient and resistive-g modes. We also note several generic issues for SOL turbulence: ambipolarity of the transport, the effect on parallel transport, and the consequences of lack of separation between the fluctuation and equilibrium scale lengths.

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A Survey of Problems in Divertor and Edge Plasma Theory

Harold Weitzner for the
Divertor and Edge Plasma Theory Working Group

Our present understanding of how a magnetic fusion reactor mght operate indicates that there will be substantial energy and particle fluxes to the walls, not including the neutron flux. The control of these fluxes is a critical problem for ITER, TPX, and subsequent advanced tokamaks. At the suggestion of OFE, a working group on divertors and edge theory has been established to explore what support the U.S. theoretical program can reasonably give to the planning for proposed experiments such as ITER and TPX, and what underlying problems could be usefully addressed by the program. The group has isolated a broad-ranging list of problems of substantial importance to the control and understanding of the flows outside of the plasma separatrix. A survey of these problems will be given.

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Divertor target geometry effects on tokamak edge plasmas*

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*Work supported by U.S. DOE Contract DE-FG03-86ER-52130

The UCLA-EMS (Edge Modeling System) computer code is used to analyze the effects of geometry variations on the diverted plasma edge of a fusion tokamak. In the case of nonorthogonal flux-surface/target intersection, the standard anisotropic fluid model used routinely for edge computations has ill-posed boundary conditions. This anomaly appears in the numerics as an overspecified outflow condition on the parallel density transport, and numerical solution is not straight forward, as in the perpendicular case.

The problem is studied using multiple stencil arrangements, all within the solving ability of the EMS code. We try various five- and nine-point second order stencils with a first order convection operator for simplicity. Proposed solutions are given in reactor relevant regimes by adjusting fixed boundary conditions to minimize the outflow boundary layer.

Computational and operational aspects of model entry and discretization adjustment within the EMS structure are discussed. The code remains under active development at the UCLA/IPFR.

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An Investigation of the Large Growth Rate Limit of Tearing Modes

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By considering a model with spatial variation of the plasma density in the inner layer, we demonstrate that the usual large growth limit of resistive tearing modes is not well-behaved. In the large growth limit of resistive tearing modes, the resistivity plays a negligible role in determining the inner region behavior. Thus we describe the inner region here with the ideal magnetohydrodynamic equations while using the tearing mode formalism. In the usual matching between an inner layer and an outer region, the inertia of the outer region is ignored. Equivalently, the plasma density is taken to vanish there. Across the inner layer, the plasma density is taken to be constant. Thus there is a discontinuity in the density in the matching problem. To demonstrate the significance of this discontinuity, we have modified the inner layer equations so that the density varies across the inner layer, and vanishes outside some strictly limited region within the inner layer. This results in a large difference from the constant density model, for the function $\Delta(Q)$. Here $\Delta(Q)$ is the matching data from the inner region to be used in the dispersion relation $\Delta(Q) = \Delta'$. Even the sign of $\Delta(Q)$ can be affected.

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Origin of Radiation Emission Induced by Fusion Produced Products*

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The excitation of collective modes at the harmonics of the cyclotron frequency of the α–particle population produced in D-T fusing plasmas has been predicted on the basis of a well developed theory [1], for toroidal confinement configurations, that was intitially motivated by a search for collective modes in fusing plasmas with spin polarized nuclei. The mode excitation is due to a resonant interaction involving a special kind of compressional Alfvén mode, with a characteristic radial profile and a frequency equal to a multiple of the α–particle cyclotron frequency, and a locally anisotropic distribution in velocity space of the high energy α–particle population. These modes are shown to be spatially localized in a narrow layer centered on a surface near the edge of the plasma column. The evaluated position of this surface is quite close with that estimated from the value of the magnetic field that corresponds to the peaks of the radiation emitted by the D-T plasma produced in the JET machine [2], when the frequencies of these are identified with the harmonics of the α–particle cyclotron frequency. The width of the layer is compatible with the relatively narrow width of the peaks in the emitted spectrum.

The outermost edge of the plasma is reached by the alpha particles with magnetically trapped orbits of relatively large amplitude and with a velocity distribution anisotropy of the type needed to drive the modes unstable – specifically, particles with large ratios of $v_\perp/v_\|$. The effect of these modes is to scatter the resonating particles and decrease their pitch angle $v_\perp/v_\|$, thus decreasing the radial widths of their orbits [3]. It is suggested that this emission process can be utilized to measure the single particle confinement of the charged fusion products as a function of the plasma current. In addition, RF waves at the harmonics of the α-cyclotron frequency, could be injected in order to influence the particle orbit width and the α-particle distribution in velocity space.

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Computer Simulation of Transport Driven Current in Tokamaks*

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

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

The Bootstrap and dynamo mechanisms do not drive toroidal current where the poloidal magnetic field is zero; therefore, the Bootstrap Theory asserts that a "seed current" must be maintained by some other means at the magnetic axis. Our simulations, as well as initial theoretical work, indicate that in tokamak plasmas, various processes naturally transport current from the outer regions of the plasma to the magnetic axis. The mechanisms which cause this effective electron viscosity include conventional binary collisions, wave emission and reabsorption, and also convection associated with $\vec{E} \times \vec{B}$ vortex motion. The simulations also exhibit preferential loss of particles carrying current opposing the bulk plasma current. This preferential loss generates current even at the magnetic axis. If these self-seeding mechanisms function in experiments as they do in our simulations, then transport driven current would eliminate the need for any external current drive in tokamaks, except simple ohmic heating for initial generation of the plasma.

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Gyrokinetic simulation in a general metric*

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We apply the gyrokinetic equation of Dubin *et al* to the electrostatic simulation of plasmas in a general coordinate metric, via the Toroidal Particle Code (TPC). The metric-dependent terms are retained without approximation in our treatment. In a non-Cartesian metric, the gyrokinetic Poisson equation takes an integral form. The shielded potential appears in the Poisson equation in slab geometry as $[1 - \Gamma_0(k_\perp^2 \rho_i^2)]\Phi(\mathbf{k})$, and can be accurately modeled through order $k_\perp \rho_i \gtrsim 2$ using a Padé approximant for the modified Bessel function. These extra terms then appear as second order differential operators. An algorithm for iterative solution of the resultant field equation is examined in detail. The gyroaveraging of the ion density and interpolated electric field is accomplished by a variant of the usual four-point method, generalized to arbitrary metrics. The effect of plasma density and temperature profiles on the field equations, convergence of the field solver, and underlying physics of η_i mode fluctuations and transport will be discussed.

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INFLUENCE OF TRAPPED THERMAL PARTICLES ON GLOBAL n=1 MODES IN HIGH TEMPERATURE TOKAMAK PLASMAS

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Energetic trapped particles are known to strongly modify the stability properties of the $n = 1$ internal kink mode in tokamaks. In high temperature discharges, similar interactions involving thermal particles can be shown to be important. When considering such interactions, it is essential to include the coupling to electrostatic perturbations that give rise to perturbed parallel electric fields. Thus, one is led to investigate the interaction between magnetic, MHD like modes and electrostatic trapped particle modes. In order to study this interaction, we have modified the global stability code MARS to include the effects of trapped particles, both ions and electrons, and electrostatic perturbations. Using the code, we have investigated the stability of various profiles for circular and JET-shaped cross sections. The stability of the pressure-driven, ideal $n = 1$ mode is strongly modified by the trapped particles. When the electrostatic potential is neglected, the trapped particles are generally stabilizing. However, with only one trapped species (electrons or ions), cases unstable in ideal MHD remain unstable and the mode acquires a significant rotation frequency. With both species of trapped particles treated by drift kinetic theory, the rotation is much reduced and the mode is stabilized well above the ideal-MHD threshold. If the electrostatic potential is retained, the mode structure can be strongly modified by the trapped particles via coupling of the $m > 1$ side-bands to trapped particle modes, and the stabilizing effect is lost. Additional results will be presented showing the dependence of the mode's stability on the relevant parameters as well describing the method by which the governing equations are solved numerically.

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Identification and Solution of the Generic Linear Mode Conversion Problem in One Dimension†

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Many authors[1-4] have investigated certain classes of equations known to exhibit linear mode conversion. The choice of which equations to investigate has been guided largely by heuristic arguments, and this has led to some confusion about exactly which equations should exhibit mode conversion. We take a more general approach to the problem of linear mode conversion by considering all multi-component linear Hermitian wave equations. Within this class of equations, we identify the type of mode conversion which most frequently occurs (from a genericity standpoint), and then use a normal form transformation[5] to find an explicit asymptotic solution for all equations in this class which exhibit generic mode conversion.

We find that generic mode conversion is pairwise and local; in the (small) region of wave phase space where it occurs, it is characterized by a 2×2 Hermitian dispersion matrix $D(x,k)$ which is linear in x and k. Writing

$$D(x,k) = \begin{pmatrix} B^0(x,k)+B^3(x,k) & B^1(x,k)-iB^2(x,k) \\ B^1(x,k)+iB^2(x,k) & B^0(x,k)-B^3(x,k) \end{pmatrix},$$

where the B^μ, $\mu = 0,1,2,3$, are real, the conversion coefficient C for generic linear mode conversion is

$$C = 1 - e^{-2\pi\nu}, \quad \nu = \left. \frac{|B^\mu B_\mu|}{|2\{B^\mu, B^\nu\}\{B_\mu, B_\nu\}|^{1/2}} \right|_{x_0,k_0}.$$

Here $\{,\}$ is the Poisson bracket, (x_0,k_0) is the point in the mode conversion region where $\det D(x,k)$ is stationary with respect to variations of x and k, we sum on repeated indices, and we raise and lower indices with the Minkowski metric $\eta^{\mu\nu} = \mathrm{diag}(+1,-1,-1,-1)$.

To illustrate our results, we have applied them to a model for mode conversion between electromagnetic and electrostatic waves in the ionosphere.[6]

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† Work supported by the Office of Fusion Energy and the Office of Basic Energy Sciences of the US Department of Energy under contract No. DE-AC03-76SF00098.

SHERWOOD THEORY MEETING 1993

A Generic Coordinate System and a Set of Generic Variables for the MFE Database*

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Over the last several years, profile data from nine different tokamaks have been stored in the magnetic fusion energy database (MFEDB). These data sets have come from a variety of sources and most are given in different coordinate systems. In order to attempt any intermachine analysis, it is convenient to transform these data sets into one generic coordinate system and to choose a uniform set of variable names. We describe the data sets from each tokamak indicating the source of the data and the coordinate system in which it is given. Next, we discuss the generic coordinate that has been adopted and show how it is implemented for each tokamak. Finally, the generic naming convention that has been adopted is discussed. It follows closely that which was used by Christiansen *et al.*[1] for the ITER Global Energy Confinement H-Mode Database. For further clarification, we discuss the characteristics of the magnetic geometry given a Fourier representation of the magnetic equilibria.

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* Supported by USDOE Grant DE-FG05-88ER53266

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Three Religious Rules of Nonlinear Physics*

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The theory of strong turbulence is a part of nonlinear physics. The three "religious rules" of nonlinear physics present a heuristic viewpoint that can be used to qualitatively predict the evolution of nonlinear systems. These rules are as follows.

1. The basic results can be obtained from the conservation laws. If some kind of process is not forbidden by these laws, it generally occurs. If it doesn't, this means that we are missing another conserved quantity imposing the constraint.

2. The universal law of "20/80" takes place: 20% of people drink 80% of beer. In other words, interesting processes usually take place in localized structures occupying a small share of volume. The localized structures interact weakly and therefore maintain their identity. For this reason they are universal and can be investigated.

3. The "general situation" is nonintegrable. The special cases of exact solutions in integrable models represent a degenerate (nontypical) behavior. Particular exact solutions cannot be taken as representative solutions unless they are attractors. The presence of attractors simplifies the analysis and clarifies the situation.

In plasma physics we deal with infinite-dimensional (PDE) systems distributed in space. The application of the religious rules 1 and 2 then leads to the following.

If the conservation laws do not prohibit the development of singularities they do occur. If the singularities are prohibited, then stable localized structures take place. Solitons (or solitary waves) and vortices are examples of such stable structures. Wave collapse, wave-breaking, shock waves, magnetic reconnection, and singularities in ideal Euler liquid are the examples of singularities.

According to rule 3, exact solutions are very essential if they are attractors in some sense. Analysis of this problem will be presented for solitons in nonintegrable wave systems and 2D vortices. The concept of statistical attractor in Hamiltonian systems will be introduced.

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Non-Vanishing Fast-Ion Bootstrap Current on Axis

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Bootstrap Current, induced by isotropic fast ions, has been investigated recently[1], including the effects of finite aspect ratio, and both the drag and pitch angle scattering. Using Ampere's law to self-consistently solve for the equilibrium yielded an alpha-bootstrap current of about 7.2% that of the conventional bootstrap current for ITER-like plasmas. However, the real importance of alpha-particle bootstrap current may lie in providing a non-vanishing 'seed' current at the magnetic axis. In this work, we determine the bootstrap current using two methods: (1) using the bootstrap expressions of Ref [1] with an added nonvanishing analytic form of the alpha-bootstrap current on axis[2] solved self-consistently with a 2-D equilibrium program (2) using a fast ion gyro-center following computer code. The effects of finite banana orbit width on the fast-ion bootstrap current are then investigated.

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Bootstrap Current of Transition Particles

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Abstract

Transition particles make transitions back and forth between the toroidally and locally trapped states. The transition probability gives the relative rate of toroidally trapped particles to become locally trapped. For high energy particles or in the case of the electric potential comparable with the temperature of bulk plasma, the transition probability can be quite large, i.e. close to unity. The transition orbits then consist of one branch corresponding to the locally trapped state and another, on which the particle is toroidally trapped. Since in the locally trapped state the particle moves almost vertically, meanwhile it always moves in some particular toroidal direction in the toroidally trapped state, such orbits should modify the longitudinal transport, bootstrap current in particular. In our work we evaluate the bootstrap current corresponding to such transition particles.

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Visualization Strategies In Tokamak Fluid Turbulence Studies

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Computational model development represents an essential part of fusion research. The time and effort needed to assess and improve these models depends critically on the realism and complexity of the model and, in particular, on the capability and capacity of computing resource brought to bear on the problem.

Not only must we ask "How much computation can we realistically expect to do with a particular resource?", but we must further assess "How much computation can we, in actuality, realize from this resource in a day?" In this context, a day is the turn-around time, the psychological scope appropriate for running a simulation, reducing the results to palatable form and assessing the need for changes to the model.

With more computer and communications resources, the complexity, the realism, and the resolution of the models we can hope to refine on a fixed psychological timescale increase only with a commensurate increase in our ability to grasp and integrate the behavior produced by simulation. A successful strategy to help us retrieve, understand and compare model behavior under the action of model development will likely need to use the increased power of the computing resource itself to create visual experience. The impact of the experience will depend strongly on the craft used in its creation.

Some elements of an artful strategy might include the appropriate use of geometrical cues and frame construction to support familiarity. Navigational freedom can be used to orient and contextualize scenes and to discover developmental changes across data sets. It is also a natural precursor to animation. Clarity rests on the balance struck between relational complexity on the one hand and detail on the other. Visual analysis tools for feature extraction, tracking and classification provide a powerful aid for culling data to achieve that balance.

Trying to bring the analysis, model development and assessment, execution and improvement cycles into a realistic daily working schedule involves using more powerful computer supported collaborative work communications and analysis tools. A computer environment which supports generating and storing enormous quantities of data, but lacks the powerful data navigation and visualization tools necessary to determine quickly and effectively whether the data should be archived or destroyed soon becomes dysfunctional.

The idea is to provide a powerful enough data reduction facility to match the data generation capability of the mainframes on the one side, and the high information content interactivity demands of the researcher on the other.

Quasistatically Evolved Toroidal Equilibria*

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Efficient numerical simulation of tokamak plasma discharges must exploit the large separation of transport and Alfvén timescales. The Grad-Hogan prescription[1] accomplishes this by evolving flux-surface-averaged transport equations for particle density, entropy density, and magnetic flux, coupled to the Grad-Shafranov equation for MHD equilibrium. A complete and self-consistent model must also evolve the circuit equations for the PF/OH coils, the passive conductors, the active control coils, and the measuring loops. The MHD equilibrium must be solved as a free-boundary problem consistent with the currents in these coils.

We are developing a transport code using these ideas. This code evolves (on the slow timescale) the 1D transport equations and the circuit equations. LLNL's TEQ (Toroidal EQuilibrium) code is used to solve the free-boundary equilibrium problem. We will present preliminary results from the time-dependent code. Furthermore, TEQ has been modified to solve for equilibria given the q and entropy density profiles, which allows the code to follow adiabatic (transport-free) transients. Applications to vertical events and disruptions will be discussed. In particular, we will compare results from TEQ's linear variational vertical stability package with those from the time-dependent code.

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

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Neoclassical Theory of Poloidal and Toroidal Rotations

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Neoclassical theory for poloidal and toroidal rotations in Tokamak plasmas in the plateau and banana regions is derived. We found that the acceleration of poloidal rotation in the plateau region is faster than that in the Pfirsh-Schluter region (Stringer's Spin-up) by a factor of the order of $(m_i/m_e)^{1/2}$ due to the much larger contribution to the parallel force acting on the plasma by the resonant ions than that by electrons. This, however, does not lead to Stringer-Spin-up-type instability. Eventually a steady state radial electric field is established. Accompanying this very large acceleration of poloidal rotation in the plateau region, we propose a plausible explaination of the recent experimental observation of D III D plasma which shows that transition from L to H occurs when the edge ν_{*i} is reduced to unity.

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

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We examine analytically and numerically a two-field fluid model for the 2-D collisionless trapped-electron mode (CTEM) with the goal of understanding real and spectral space dynamics as well as the relationship of these dynamics to the driven particle transport. This model evolves both trapped electron density and electrostatic potential, with nonlinear dynamical effects of ion polarization, ion $E \times B$ and electron $E \times B$ nonlinearities. Through numerical elimination of the various nonlinearities we are able to isolate the effects attributable to each. Principle results can be summarized as follows:

1.) When the ion and electron $E \times B$ nonlinearities are 'turned off,' the particle transport and fluctuation levels increase by a factor of ten.

2.) Whereas the full CTEM shows isotropic spectra, these become anisotropic in the absence of the nonlinearities. In addition, there is a downward shift in rms wave number.

3.) The kinetic energy flow direction (at lower wave numbers) changes with and without the nonlinearities. This is consistent with the observation that the change in the spectral shape is mainly at low k.

Preliminary results of frequency spectra indicate large real frequency shifts compared to linear, similar to Waltz.[3] Frequency spectra do change minimally due to the electron nonlinearity, but not enough to account for large changes in transport.

These results have a number of implications including the gross overestimation of fluctuation levels, transport and rms wave number by '$i\delta$' models. Further, it can be surmised that electron dynamics play a key role in spectral transfer and that the character of the CTEM saturated steady state changes fundamentally with electron dynamics. We further note that through these studies, we are able to provide a guide to the possible signature of the CTEM model for experimental observation, i.e. isotropy, spectral peak, and nonlocal vs. local nonlinear transfer.

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Atomic Physics Modifications of Braginskii for Divertor and Edge Plasmas in Tokamaks

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Fluid descriptions of the divertor and edge regions of tokamaks are complicated by the need to retain neutrals and their coupling to the plasma by such processes as charge exchange, electron impact ionization and excitation, and recombination. By examining somewhat idealized kinetic models one can gain important insights into the effects of the neutral-plasma coupling and its impact on transport and ambipolarity. Recently, Hazeltine *et al* [1] investigated a model for the neutral-ion coupling which retains charge exchange, impact ionization, and recombination. By neglecting the temporal evolution, considering small mean flows and assuming charge exchange dominates over ionization and recombination, they were able to show that in the small mean free path limit the neutral viscosity is much larger than that of the ions in the edge region. A more general ordering permitting time variation, large mean flows, and ionization and recombination comparable to charge exchange will be considered by a procedure that combines the techniques of Braginskii [2] with the model of Hazeltine *et al.* The simplicity of the resulting equation for the first order ion distribution function allows all of Braginskii results to be adopted with only minor modification. The further assumption that the product of the charge exchange cross section times the relative speed is independent of velocity [1] gives tractable results for the neutrals as well.

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Simulation of Radiative Divertor Flame Fronts and Supersonic Flow*

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The Radiative/Gaseous divertor is currently the most promising concept for handling the high scrape-off layer power flows in the International Thermonuclear Experimental Reactor (ITER). We are performing 1-D and 2-D edge plasma fluid simulations to study the feasibility of this divertor concept. We are currently using the 1-D (along B) code NEWT-1D and the 2-D code NEWEDGE. NEWT-1D solves a separate continuity and momentum equation for each charge state of a given impurity species in a self-consistently evolved background plasma. NEWEDGE solves a single "average impurity" continuity equation assuming an inertia-less, viscosity-free momentum equation, along with the standard Braginskii equations for the hydrogen background. This "average impurity" transport description will be described along with the accompanying non-equilibrium radiation model. Results from the two codes will be compared for simulating the flame front in a radiative/gaseous divertor. Results which show transition to supersonic flow across the flame front will be presented and discussed. Results of impurity entrainment in the divertor region will also be presented.

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STOCHASTICITY AND RECONNECTION IN AN AREA PRESERVING NONTWIST MAP*

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Area preserving maps are useful models for studying the stochasticity of magnetic field lines in tokamaks in addition to transport problems in plasmas and fluids. In most cases (i.e. the Taylor-Chirikov standard map) the map is assumed to satisfy the so called twist condition according to which the periodic variable of the map is a monotonic function of the other map variable. However, there are physical systems that naturally yield nontwist maps; for example, the stochasticity and reconnection of magnetic field lines in a tokamak with a non-monotonic q-profile [1] and the chaotic transport by traveling waves in a symmetric shear flow [2]. In the present work we study a nontwist map for which the twist condition is violated along a curve, called the shearless curve. One of the distinct features of the nontwist map is the possibility of separatrix reconnection of islands across the shearless curve. The study of the destruction of the shearless curve is a complicated and interesting problem since in the vicinity of such a curve most of the known results and techniques concerning area preserving maps fail to apply. We study numerically the role of reconnection in the destruction of the shearless curve. By writing the map as a product of two involutions we construct the symmetry lines of the map and use them to find the location of periodic orbits. An attempt is made to relate the destruction of the shearless curve to the behavior of the nearby periodic orbits.

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The Role of Self-Consistent Lagrangian Chaos in Benard and Interchange Convection

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The nonlinear behavior of the 2D Benard problem with periodic boundary conditions in the horizontal direction, a model for interchange modes in the tokamak edge region, has been studied[1] with the aim of understanding the L-H transition and ELMS. The results[1] show a complex interplay between vortices driven by the Rayleigh-Taylor instability and shear flow[2] which is driven the vortices and which causes their decay. In this paper we study the transition from the low Rayleigh number (Ra) regime to the high Ra regime. For the former, vortex flow and shear flow coexist, possibly with slow relaxation oscillations. In the high Ra regime there are vortices localized near the upper and lower boundaries with a shear flow in between. As Ra is decreased, these vortices broaden, eventually overlapping, causing self-consistent lagrangian chaos. This onset of chaos is responsible for the transition to the low Ra regime. In the low Ra regime, on the other hand, the relaxation oscillations are on a much slower time scale than the eddy turnover time and the lagrangian behavior is described by separatrix crossing.

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Beam and Impurity Effects on the Ion Temperature Gradient Mode*

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Recently, many comparisons between the experiment and the theoretical models of the ion thermal conductivity appears to require theorists to consider more realistic models of the plasma. Here, as one such effort we study the effects of high energy beam ions and the impurity ions on the ion temperature gradient (ITG) modes. In this study, we use the full kinetic theory where the finite ion Larmor radius (FLR) effect and the resonance effects by the parallel transit drift and the toroidal curvature drift are fully consdered for all ion species. For the beam ions, we consider two models of the velocity distribution functions; the simple Maxwellian and the slowing down distribution. It is found that the main effect of beam ions comes through the dilution of main ion density, giving a signficant stabilization on the ITG mode. The effect of the impurity ions appears to be more complicated than the beam ions. In the limit that the impurity element dominates the working gas, the impurity ITG mode which has the smaller threshold η_c value but the smaller growth rate at $\eta \gg \eta_c$, can be driven. When the charge density fraction of the impurity to the main ions increases from 0 to 1 the charactersitic of mode changes *continuously* from the main ion mode to the impurity mode. Maximum stabilization occurs usually when the mixtures of two species are almost equal in terms of the charge density contribution. We will also discuss the impurity effect on the particle flux of main ions using the quasilinear theory.

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WHAT IS THERMODYNAMIC EQUILIBRIUM FOR A NON-NEUTRAL PLASMA IN A DC MAGNETIC FIELD?

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We consider the most-probable (maximum entropy) state of a non-neutral, two-species, Vlasov plasma inside a smooth cylinder embedded in a uniform dc magnetic field in the axial direction. The problem is motivated by several experiments in which fluid velocities have been inferred from E x B drifts, using measured radial electric fields. The axisymmetric most probable states are obtained by solving numerically a (positive temperature) nonlinear Poisson equation for the scalar potential. Though omitting several features of real-life operation of a tokamak, the problem has some interest because of its exact solubility. There are two independently conserved quantities in addition to the energy: axial angular momentum and total plasma charge. The angular momentum controls the fluid velocity and the total charge (by Gauss's law) controls the radial electric field at the wall. Thus the two velocities cannot agree everywhere, except in special cases. The result is a boundary layer near the radial boundary of the plasma in which the drift velocity and the fluid velocity (always a rigid rotation, in thermal equilibrium) can sharply disagree. The plasma electron density departs from uniformity in this boundary layer. Using E x B drifts as fluid velocities in the boundary layer would lead to the erroneous inference of shear in the fluid velocity field. It is expected that differences will persist even for plasmas not in thermal equilibrium. Not all velocity shears may be fictitious, but caution is advised in inferring them from drifts.

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Isotope Effect and Charge-Exchange Energy Loss

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The isotope effect, which is the improvement in confinement of deuterium over hydrogen plasmas, is observed in some tokamaks but not in others. Neither collisional nor turbulent transport predict this, because they both lead to higher transport for the larger mass (A) with the larger gyroradius. On the other hand, neutral mean free paths decrease with increasing mass. We find that the local ion thermal conductivity due to charge-exchange scales like A, and is much larger than neoclassical conductivity. We study its impact on global confinement to see if it can explain the interesting puzzle that the isotope effect is observed in some machines but not in others.

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2C23

Ponderomotive Force Induced by Wave Absorption

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Radiofrequency heating and current drive in hot plasmas can lead to localized absorption profiles, and strong gradients can appear in the electromagnetic field amplitude as a consequence.

Considering a high frequency wave, and propagation in a homogeneous magnetized plasma, it is possible to solve the Vlasov equation for the "slow" part of the distribution function in the quasilinear approximation, for finite wave damping.[1] Expanding the distribution function in harmonics of the gyrophase, and averaging over fast oscillations, results in a set of coupled equations for the quasilinear evolution of each harmonic, from which the particle flux can be obtained. The resulting equation, for the evolution of the "slow" part of the distribution function, describes *both* spatial convection, and momentum space diffusion, and reduces to the standard quasilinear equation in the limit of zero damping.

From the particle flux, the ponderomotive force is obtained in the drift approximation, and shown to reduce to the usual form for vanishing damping. For finite damping, a power series representation of the ponderomotive force in the parameter $\lambda'' = N''_\perp \left(\omega/\omega_{ce}\right)\left(p_\perp/m_e c\right)$ is given, which is convergent for $\left|\lambda''\right| \le 1.2$. The corresponding heat flux and pressure tensor are derived as well.

The main result of the work is showing that wave absorption directly induces particle and energy transport.

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Inertial-Electrostatic Confinement Studies*

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Inertial-Electrostatic Confinement is one of the earliest plasma confinement concepts, having first been suggested by P. T. Farnsworth in the 1950s. The concept involves a simple apparatus of concentric spherical electrostatic grids and intricate physics. An electrostatic structure is formed from the confluence of ion beams with a background of electrons that are provided by the grid.

New results that shall be presented are: a detailed comparison between single grid systems and two grid systems with dispenser cathodes, a conceptual design for an IEC neutron source, and an advanced concept for generalizing IEC configurations to three dimensions with both electric and magnetic fields.

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3D Toroidal Gyrokinetic Simulation of ITG Driven Turbulence

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A fully operational three dimensional electrostatic toroidal gyrokinetic simulation is now available to study tokamak turbulence and transport. Global 3D simulations with more realistic tokamak parameters ($a \sim$ 100-200ρ_i) have now become feasible because of recent advances in both low noise numerical techniques[1] and massively parallel supercomputing. This 3D Toroidal code has been used to investigate the ion temperature gradient (ITG) driven instability and the associated nonlinear behavior. The ions are fully gyrokinetic, and the electrons are treated as adiabatic. Results from the 3D toroidal simulations will be presented. In the initial phase of the run, we observe a clean linear growth of the most unstable toroidal harmonic and the associated 2D eigenmode in (r, θ) with a ballooning type structure where $k_r \ll k_\theta$. These results are in good agreement with the linear eigenmode calculations of Rewoldt and Tang[2]. In the turbulent steady-state, both long and short wavelength fluctuations are enhanced, and the ballooning structure is reduced, but still predominant. Broad scale (many modes present) turbulence with fluctuation a level of $e|\phi_k|/T \lesssim 1\%$ is observed. The k_r, k_θ spectrum show similar features as those obtained from recent beam emission spectroscopy measurements on TFTR[3], where the k_θ spectrum peaks are $k_\theta \rho_i \sim$ 0.1-0.2 and the k_r spectrum peaks at zero. Also discussed, will be the χ_i scaling (Bohm vs. Gyro-Bohm) for the turbulent steady-state. Global simulations of this type are well suited for studying Bohm like diffusion since the lowest toroidal and poloidal harmonics are fully resolved.

Another simulation model which uses field line following coordinates to simulate a flux tube has also been developed. This model greatly reduces the volume of the simulation domain, and hence, the computational requirements. It does however, require imposing more theoretical assumptions (e.g. $\Delta r/r_0 \ll 1$, $r/(qR) \ll 1$, $\frac{\Delta r}{q}\frac{dq}{dr} \ll 1$, where Δr is the radial width of the domain). Results from this simulation will also be presented. In the future, we plan to add drift kinetic electrons and finite beta effects ($\delta B_\perp$) to these toroidal codes greatly extending their applicability.

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Ballooning Modes in Linked Mirror Configurations*

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A toroidally linked mirror system has recently been proposed as a neutron source.[1] Two parallel pairs of minimum-B mirror cells are linked by two semitori with cross sections having high ellipticity.

Large elongation of the cross-section perpendicular to the toroidal radius of curvature can lead to easier line-bending in the bad curvature region, resulting in relatively lower toroidal beta (β_τ) limits due to short wave-length ballooning instabilities. However, kinetic effects can stabilize such modes with short perpendicular wavelengths, and the most unstable modes are likely to have long wavelengths.[2] We explore both regimes to obtain estimates of the critical β_τ limits.

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Arbitrary Mode Number Boundary Layer theory for Non-Ideal Toroidal Alfvén Modes

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Previous studies have shown the significance of finite parallel electric field and finite Larmor radius on the wave structure and damping of a single isolated TAE,[1] pointed out the possible importance of a new kinetic TAE (KTAE),[1] and have developed an asymptotic matching/boundary layer procedure to incorporate these non-ideal effects in high mode number multiple-gap configurations.[2] The present work generalizes the description of TAE and KTAE to arbitrary mode number for the model of a large aspect ratio low-beta circular tokamak with appropriate boundary conditions. The mathematical machinery developed here is found to describe a rich spectrum of TAE and KTAE. Detailed analytic descriptions using WKB theory and other approximations are found to accurately describe both TAE and KTAE over a wide range of parameters. These analytic descriptions also provide insight into the competition between the resistive damping and that due to radiation of Kinetic Alfvén waves (KAW). The radiative damping is frequently found to dominate the damping of the TAE, but not the KTAE. For small nonideal parameters, the KTAE modes are found to occur in pairs.

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Instability Due to Axial Shear and Surface Impedance*

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The stability of plasma flow in the scrape-off layer of a tokamak, taking into account the surface sheath impedance and the axial shear in the $E \times B$ flow is analyzed. An interesting stability criterion arises in the limit that end plates are sufficiently far apart, so that stability can be analyzed when the plasma is taken to interact with a single end plate. It is conjectured that the stability of this problem may be of relevance to establishing H-mode conditions in diverted tokamak plasmas.

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1993 Sherwood Theory Meeting

SOLUTION OF THE DRIFT-KINETIC EQUATION FOR GLOBAL PLASMA MODES AND FINITE PARTICLE ORBIT WIDTHS

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The response of a collisionless plasma to global electro-magnetic perturbations of an axisymmetric toroidal equilibrium is derived. By adopting a variational formulation for guiding centre motion, the perturbed distribution function is expressed in terms of the linearised particle Lagrangian. Finite orbit widths are retained. In particular, the high particle energy limit where mirror-trapped "banana" orbits are distorted into "potato-shaped" orbits is considered [1]. In this limit, the time scales associated with the drift and bounce motions of a trapped orbit become comparable, yielding important consequences on plasma stability. Quadratic forms are constructed in the context of kinetic-MHD models of plasmas composed of a thermal component obeying fluid-like equations and a high energy component described in terms of the collisionless drift-kinetic equation. Relevant applications include improved modelling of energetic ion effects on toroidicity - induced Alfvén gap modes and internal kinks.

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Gyrokinetic Simulations in Toroidal Geometry.[1]

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We have previously reported gyrokinetic simulations of toroidal ion-temperature-gradient turbulence in which the main toroidal drive, the poloidal component of the toroidal drift, and the toroidal coupling due to its poloidal dependence were included.[2] The definition, implementation, and advantages of quasiballooning coordinates[3] have also been previously reported. For the simulation of instabilities and turbulence with a ballooning structure, in radial regions wider than the two-dimensional sheared slab Landau damping scale, they allow a large reduction in the number of grid cells needed to obtain a given spatial resolution, compared with toroidal-poloidal and other unsheared coordinate systems.[4] There is also a consequent optimization of timestep requirements in explicit codes and of the noise spectrum in particle codes. These efforts are being extended and merged to produce a fully toroidal partially-linearized gyrokinetic particle code that includes the radial as well as the perpendicular components of the toroidal drifts. A key issue is the choice of radial boundary conditions. By making the simulation periodic in the radial quasiballooning coordinate, the radial boundaries are connected in such a way that the magnetic field direction has no discontinuity. This choice prevents both quasilinear profile relaxation and the accumulation of particles that exit and enter the radial boundaries due to the radial component of the equilibrium magnetic drifts. Simulation results including the toroidal drifts and trapped ions will be presented. Results that address the effect of *poloidal* flow damping on the *perpendicular* $\boldsymbol{E} \times \boldsymbol{B}$ flow-generation mechanisms previously observed[5] will also be presented.

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Finite Beta Induced Gaps in the Toroidal Alfvén Spectrum

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In the DIII–D neutral beam injection experiment [1,2], MHD oscillations at frequencies both above (in the TAE gap) and below (in the finite β gap) the lowest branch of the Alfvén waves have been observed. Their frequencies correspond closely to those predicted by the global ideal MHD codes [3]. Although TAE modes have been predicted theoretically to be formed and exist in the first gap, the nature of the oscillations in the finite β gap remains unclear. This also calls for a reexamination of the finite β effect of the Alfvén spectrum [4].

In the MHD model, the lowest branch of the toroidal Alfvén wave spectrum is substantially complicated by the coupling with the ion acoustic waves excited through the geodesic curvature coupling. This coupling induces gaps in the Alfvén wave spectrum, with the gap size proportional to $q\,\beta^{3/4}\,\bar{\kappa}$, and the Alfvén waves obtaining increasingly large sound wave polarization. With the inclusion of kinetic effects, the plasma compressibility is modified and the sound waves are damped, resulting in modifications to the gap structure. The effect of these on the global mode and the ion Landau damping processes will be discussed.

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Anomalous Energy Pinch In Turbulent Transport *

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In the interpretation of experimental data for plasma confinement in tokamaks the density flux is often assumed in the form $\Gamma = -D\nabla n + V_0 n$. The second term in this expression is responsible for the pinch effect in a particle flux. Much experimental data[1] shows that a similar pinch term in the energy flux is quite useful in explaining the density and temperature profiles observed in tokamaks. The Ware pinch that exists in neoclassical theory has been found to be too small to fit the experimental results. The quasilinear modification[2] of the Ware pinch does not lead to an essential enhancement of the pinch effect for symmetric spectra of turbulence. In this work we address the issue of an anomalous pinch caused by turbulent fluctuations in a tokamak plasma. In a Hamiltonian system the evolution of the ensemble averaged disribution function is governed by a Fokker-Planck type equation with a symmetric diffusivity matrix and zero friction force. From a general point of view, the pinch terms in real space originate from the off-diagonal terms of the diffusivity matrix in phase space. We consider the general structure of the quasilinear diffusivity matrix for a turbulent plasma in a toroidal plasma. We have found that for typical microinstability fluctuations this process yields an energy pinch which scales as $V_0 = D_B \epsilon q \rho / L_n$, where $D_B = cT/eB$ is the Bohm diffusion coefficient, $\epsilon = r/R$ is the inverse aspect ratio, ρ is the ion Larmor radius, L_n is the inhomogeneity scale and q is the safety factor.

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ANOMALOUS ELECTRON STREAMING DUE TO ELECTROSTATIC MODES IN TOKAMAK PLASMAS*

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The motion of circulating electrons in a tokamak interacting with electrostatic waves (such as lower-hybrid waves) is given by a guiding center Hamiltonian and studied by numerical integration. The unperturbed motion of electron guiding centers is first shown to be integrable, and, in a manner similar to that used in previous works [1,2], a set of action-angle coordinates for the orbits are derived which take into account finite aspect ratio and noncircular plasma cross section. Electrostatic modes in the low-frequency, long-wavelength limit are treated as a perturbation to the guiding center Hamiltonian. The waves are generated with low integral values of the toroidal and poloidal mode numbers n and m and satisfy the approximate lower-hybrid dispersion relation $k_\perp/k_\| \approx \omega_{pe}/\omega \sim 10^{1.5}$. If the number of modes is greater than three, the electron motion parallel to the magnetic field is observed to be stochastic in the phase-space region where $v_\|$ is near the wave parallel phase velocity. On surfaces with rational values of the safety factor q, superposition of modes with degenerate values of the parallel mode number $n+(m/q)$ is shown to result in electron streaming perpendicular to the magnetic field. The speed and direction of this radial motion are observed to have sinusoidal dependence on the poloidal angle. For models including finite magnetic-field shear, we find a limit to the extent of the radial streaming of the electrons. Results for the speed of the electron radial motion for typical tokamak parameters will be presented.

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Nonlinear Gyrofluid Simulation and Analysis: ITG Turbulence

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We present results from nonlinear gyrofluid simulations of electrostatic turbulence driven by an ion temperature gradient. Our model[1] is obtained by taking moments of the nonlinear electrostatic gyrokinetic equation directly, and closing the resulting fluid hierarchy with collisionless phase mixing models of Landau damping, FLR averaging and FLR-induced nonlinear phase mixing. The latter effect, in particular, is shown to reduce the thermal transport by half for a wide range of non-dimensional parameters. It resembles a velocity-dependent hyperviscosity in form, $\propto k_\perp^2 |\Phi_{\vec{k}} \vec{k} \times \vec{k}'|$. Previous fluid simulations have ignored this physical mechanism for the damping of short-wavelength perturbations perpendicular to the magnetic field. Here, we investigate this effect in more detail, and attempt to find a reduced linear dissipation model which may be sufficient for some applications.

Earlier, we reported self-generated sheared velocity flows in our 3-D, nonlinear, slab ITG simulations which contribute strongly to the saturation of the nonlinear dynamics and to the resulting fluctuation spectrum,[2] similar to studies of other types of turbulence.[3,4] We showed that constraining the electron response to be adiabatic strictly within each flux surface leads to enhanced perpendicular sheared flows. Here, we examine the effects of a modified electron response which attempts to take into account the shorting out of the radial electric field over a given region due to magnetic turbulence. Furthermore, we investigate numerical issues of the sheared flow layers, such as possible box-size effects.

We present a few recent numerical advances we have made, including the installation of radially periodic boundary conditions which take into account the sheared magnetic field and implicit time-stepping of the non-adiabatic electron equations, to allow reasonable studies of the impact of more realistic electron dynamics. We also discuss another important numerical issue, the importance of the spacing of the rational surfaces within the simulation region. We show that an artificially low thermal flux is obtained if insufficient rational surfaces are included, or if the rational surfaces are clustered in a segment of the simulation volume.

Finally, we present a short comment on the validity of our approach as recently questioned by Mattor.[5] To this end, we present gyrokinetic and gyrofluid weak turbulence analyses of drift wave turbulence and discuss their regimes of applicability.

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Thermal Runaway Due to Fast Ion Friction Driven Heat Pinch

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Standard neoclassical transport theories only consider transport associated with the standard thermodynamic forces, density gradient, temperature gradient and toroidal electric field. In neutral beam injected (NBI) heated plasma, in addition to direct collisional heating of the bulk plasma, there can be an additional thermodynamic force associated with momentum transfer from beam ions to the background plasma [1]. Parallel momentum exchange between beam and thermal ions can drive poloidal rotation in addition to the standard temperature-gradient-driven one. This additional poloidal rotation can transfer energy between thermal energy and rotational energy. Usually energy is transferred to thermal energy via viscous heating.

In addition to viscous heating, there is also a heat pinch effect due to momentum transfer from beam to thermal ions. This driven thermal ion energy flux is inward in the case of co-injection, and can be significantly larger than the standard neoclassical heat flux. The physics of this heat pinch is similar to the Ware pinch, but the former is more important in strongly NBI heated plasma.

The resultant thermal ion energy balance equation (including standard neoclassical heat conduction, beam-driven viscous heating, direct heating and beam-driven heat pinch) can be solved in steady state to determine the equilibrium temperature profile. The only steady state solution to this equation is $T_i \sim r^{-3}$, which implies thermal runaway close to the magnetic axis. The main cause of this runaway of central temperature is that the beam-driven inward heat pinch is dominant over standard conduction close to the magnetic axis. We conjecture that this thermal runaway in the case of co-injection may be the principal reason for the rapid increase of central temperature, the peaked ion temperature profile in the core region and the very low inferred ion thermal diffusivity in the Hot Ion H–modes in DIII–D. Qualitative comparison between theory and experiments will also be presented.

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Monte-Carlo Simulation Studies of Effects of Radial Electric field on Particle Motion in the Tokamak Plasma*

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The character of particle motion in an axisymmetric toroidal system is investigated by Monte-Carlo method that simulates the pitch-angle scattering, along with the charged particle guiding-center integration. Emphasis is laid on the effects of the constant radial electric field on the particle orbits and the particle transport. A radial mobility of the charged particles caused by the combined effects of the radial electric field and pitch-angle scattering is found in all collision regions. A simple moment argument involving the trapped particle population gives an analytical formula for the radial mobility of the ion in the banana regime matches the simulation results. The effects of the radial electric field shear are also studied.

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Effects of Rational Surface Density on Resistive g Turbulence*

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The Beklemishev-Horton theory[1,2] states that the anomalous transport coefficient is proportional to the density of rational surfaces provided that the interaction between the modes localized around different rational surfaces is weak compared with modes of the same helicity. We examine the effects of the density of states ρ using resistive g turbulence in 2D (single-helicity) and 3D (multi-helicity) simulations.

We find that the modes with different helicities do not equipartition the available energy, but rather the coalescence or inverse cascade effect is strong so that a few low order mode rational surfaces receive most of the energy. The quasilinear flattening at the surfaces is a strong effect and we use bifurcation theory[3] to derive that the effective diffusivity increases as $\chi_{eff} = \chi_o\rho/(1 - C\rho)$ where C is a constant determined by interaction integrals. For a sufficiently high density of states $C\rho \leq 1$, the higher order nonlinear interaction must be taken into account.

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Bootstrap Current Induced by Neutral Beam Injection

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Directly driven current induced by anisotropic source such as neutral beam injection (NBI) has been investigated in Ref [1]. This current corresponds to the odd distribution function driven by the odd source term S_-. Here, the source term is decomposed into $S = S_+ + S_-$ and the subscript '+' ('−') denotes 'even' ('odd') in pitch angle. However, we note that the radial gradient of the even part of the distribution function can also induce current known as bootstrap current. Depending on the orientation of the NBI, this current can become more important than the directly driven current. In particular, in the case of perpendicular injection, bootstrap current will be much larger than the directly driven current. Recently(2), bootstrap current induced by isotropic fast ions has been investigated by including the effects of pitch angle scattering and finite aspect ratio. It was found that the effects of pitch angle scattering play an equally important role as the effects of slowing down drag, even though the source term is isotropic in velocity space. This implies that the bootstap current will be greatly enhanced due to pitch angle scattering for anisotropic fast ion produced for instance from NBI. In this work, the bootstrap current induced by NBI is calculated by extending the work of Ref. [2] to include the anisotropic source term.

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SHEAR FLOW GENERATION AND TURBULENCE SUPPRESSION BY RESISTIVE BALLOONING AND RESISTIVE INTERCHANGE MODES

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The generation of shear flow by resistive ballooning modes and resistive interchange modes is compared and contrasted using a 3-D fluid code. The resistive ballooning modes give rise to poloidally asymmetric transport and hence drive poloidal rotation due to the Reynold's Stress as well as the anomalous Stringer/Winsor mechanism. On the other hand the resistive interchange mode can drive shear flow only through the Reynold's Stress. Our studies show that if the self-consistent sheared flow is suppressed, the resistive ballooning modes give rise to a larger anomalous transport than produced by the resistive interchange modes. Furthermore the shear flow generated by the resistive ballooning modes is larger than that driven by the resistive interchange modes due to the combined effect of the dual mechanisms stated earlier. As a consequence strong suppression of the fluctuations as well as reduction of the transport occurs for resistive ballooning modes. On the other hand , for the resistive interchange modes the level of fluctuation as well as the anomalous transport is not reduced by the self consistent shear flow generated by the Reynold's Stress. This latter result is in agreement with some earlier 3-D simulation of resistive interchange modes.

Tearing Mode Stability in Tokamaks with Shaped Plasma Cross-Sections [1]

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In tokamaks, magnetic perturbations with different poloidal mode numbers are coupled together via toroidicity, pressure, and the shaping of equilibrium flux-surfaces [1]. The quantities Δ which determine the resistive layer response to tearing perturbations at each rational surface in the plasma are interrelated via a matrix equation. The most general form for the tearing mode dispersion relation is $(\boldsymbol{\Delta} - \mathbf{E})\boldsymbol{\Psi} = \mathbf{C}$, where $\boldsymbol{\Delta}$ is the diagonal matrix of the Δ quantities at each of the N (say) rational surfaces in the plasma, $\mathbf{E}$ is an $N \times N$ real symmetric matrix usually referred to as the E-Matrix [2], $\boldsymbol{\Psi}$ is a $1 \times N$ vector whose elements are the reconnected magnetic fluxes at the various rational surfaces, and $\mathbf{C}$ is a $1 \times N$ vector dependent on externally applied resonant magnetic perturbations. The recently developed T7 code determines the elements of the E-Matrix and C-Vector by standard shooting techniques for a large aspect-ratio tokamak with non-circular flux-surfaces. Both free boundary and fixed boundary calculations are possible.

Toroidicity, pressure, and plasma shaping are all found to reinforce the destabilising tendency of a free boundary (i.e. no wall) with respect to a fixed boundary (i.e. a perfectly conducting wall at the edge of the plasma). This is particularly the case if the free boundary plasma lies close to the ideal stability boundary for external kink modes. Thus, at realistic aspect-ratios locked modes (which do not 'see' the wall) may be significantly more unstable than rotating modes (which do). This is a possible explanation for the JET observation that a relatively small (2, 1) error field can drive a far larger (2, 1) locked mode once the rotation of the tearing frame at $q = 2$ has been arrested [3].

The electromagnetic locking torque exerted on the $q = 2$ surface by a predominantly (2, 1) error field is found to increase with both toroidicity and plasma shaping (with the q-profile held constant), indicating that tight aspect-ratio, strongly shaped plasmas are likely to be more sensitive to error field induced locked modes than large aspect-ratio circular plasmas. For error fields with substantial non-(2, 1) side-band components, sudden changes occur in the torque as the $q = 3$ and $q = 4$ surfaces enter or leave the plasma. For an error field source localised on the outboard mid-plane, the locking torque has a 'staircase' like variation with the edge safety factor, with sudden *increases* as either $q = 3$ or $q = 4$ *leave* the plasma. Such behaviour is consistent with observations on JET [3].

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Space-Time Statistics of Drift Wave Turbulence*

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Recent probe studies[1] in TEXT-U using conditional probability statistics have shown (i) Gaussian-like statistics [kurtosis 3.1, skewness 0.1] and (ii) correlation decay rates in time and space with a finite dependence on the amplitude of the floating potential condition. Motivated by these experiments, we have modeled the turbulence as a gas of interactive vortices and waves. We compute correlation functions when conditioned by the requirement that the amplitude of the reference signal exceed a level appropriate for vortex trapping. The work extends our earlier study[2] of the statistics of drift wave turbulence. The important conclusion emerging from the experimental data, and shown here to follow from the computer simulations is that turbulent fields with Gaussian-like space-time statistics as measured by the kurtosis and skewness can be composed of a gas of interacting vortices satisfying the trapping condition. The condition for Gaussian-like statistics is that the vortex gas not be too dilute. A general formula for the relative contributions of the waves and the vortices (or coherent structures in the presence of magnetic shear) is given. In the absence of waves the condition reduces to the requirement that the packing fraction $f_p = n_v\pi \langle R^2\rangle > 1/3$ where $n_v = N_v/L_xL_y$ is the number of vortices of radius R per unit area. The Gaussian-like statistics in the wave dominated case, are given in Ref. 1 for the dissipative (Terry-Horton) driftwave equation. The statistics for other drift wave models have now also been studied.

As an example, for the Hasegawa-Mima equation a 5×5 lattice of dipole vortices with $R = 6\rho_s$, packed at $t = 0$ to give a kurtosis of 2.8 and zero skewness, evolve by $\sim 100\ L_n/c_s$ to a state of coalescing vortices with kurtosis 3.0 ± 0.1 and skewness 0.1 to 0.2. Thereafter, the kurtosis remains in this range while a progressively slower sequence of mergings continues at constant energy (5 digits) and entropy (3 digits).

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Increasing the Capabilities of Priesche's Post-Processor for PEST*

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Much work has been done to show that the predictions of critical β with respect to linearized MHD instabilities in tokamaks are close to the operational limits that are experimentally observed.[1,2] Our general belief has been that the results of the linearized theory, the growth rate of the most unstable mode and its physical shape, should be related to the behavior of the saturated state, with the amplitude and location of the density, temperature, and magnetic field that is observed experimentally closely correlated to the growth rate and shape of the linearized perturbations that are predicted by MHD stability codes like PEST. For this reason we are continuing work on the construction of a Post-Processor[3] for analysis of the output from the PEST ideal MHD stability code.[4] At the time of the Seattle meeting of the APS-DPP,[5] we had incorporated the ability to display any component of the displacement vector, the perturbed magnetic field, the perturbed density, and $\int(\delta n/n)d\phi$ (which can be identified with Beam Emission Spectroscopy measurements if the plasma is rotating so that this integration represents time averaging). We are now making an effort to incorporate calculations of the perturbed magnetic field which would be seen in a set of Mirnov coils if the plasma were rotating. Such a calculation has shown reasonably good agreement with experiment on a PDX tokamak discharge[6] and this improvement should prove useful in analysis of experiments on other tokamaks. We intend to continue this work by reconstructing the signals that are observed in soft X-ray measurements since we have available information concerning the temperature, density, and perturbed temperature everywhere in the discharge and can integrate them over the desired beam paths. Since the PEST code is based solely on ideal MHD, one must be cautious when comparing the measurements with the actual experimental data if non-ideal effects are dominant. For example, the radial Fourier harmonics of the perturbed magnetic field vanishes at their rational surfaces; this can lead to discrepancies in the Mirnov loops comparisons as shown in reference 6. As a further consequence, magnetic islands cannot manifest themselves within the PEST eigenfunctions, thus jeopardizing the soft X-rays comparisons. However, although perturbations due *solely to nonideal effects* may not be validly compared, ideal MHD perturbations driven unstable by non-ideal forces, *e.g.* Fishbones or TAE modes, may be legitimately compared. Nonetheless, the planned inclusion of more realistic physics in the PEST system of codes will further validate our efforts. The Post-Processor is also modular enough to be incorporated in other codes which may already have non-ideal effects such as the nonlinear resistive codes. The status of the work will be described.

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A MODEL OF ENERGY TRANSPORT BASED ON ALFVEN-WAVE FILAMENTS*

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A detailed energy balance principle is developed in terms of the radiation cooling and reheat associated with the generation and absorption of Alfven-wave filaments. These elongated structures are resistively evanescent in the radial direction with characteristic length on the order of the electron skin-depth and have parallel phase velocities in the interval between the Alfven speed and the electron thermal velocity. The individual filaments are envisioned to be spontaneously generated by finite amplitude, non-equilibrium fluctuations in the electron distribution function. The two key physical quantities in the process are the radial scale length and the universal radiation resistance of the filament. A frustrated thermal equilibrium is defined as the simultaneous requirement to maximize the number of particles within a filament and the total number of filaments within the confinement device. Such an argument leads to Alcator scaling that deteriorates with increasing temperature.

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Distributed Plasma Simulation Using C++ and ESP*

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Particle in Cell codes have long been the mainstay of kinetic plasma simulation. However, they have traditionally performed poorly on vector supercomputers because of the gather/scatter required for charge weighting and force interpolation. Furthermore, development of full featured codes with the flexibility and power desired for NTP simulations is difficult in Fortran.

Using the Extensible Software Platform, an enhanced C++ environent for distributed computation, we developed a sample 1 dimensional electrostatic PIC code. We describe the ESP environment, emphasizing its support for distributed asynchronous computing using the concept of a `future`. We further discuss the implementation of the PIC code in this environment, its performance and the impact of the ESP programming model on the portability of the code.

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Onsager symmetries for nonequilibrium steady states*

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The classical derivation of the famous Onsager symmetry of the transport matrix is critically examined with particular attention to its relevance to *turbulent steady states* that may be *far from thermal equilibrium.* A distinction is made between steady-state fluxes and *incremental* fluxes resulting from perturbations around the steady state. For nonequilibrium steady states, Onsager-type theorems apply at best only to the incremental fluxes. However, recalling the seminal work of Dufty and Rubi, we note that the original Onsager symmetry is destroyed in general because the steady-state distribution function need not be invariant under time reversal. Dufty's generalized Onsager theorem is reviewed and discussed from several points of view. An explicitly soluble Langevin problem is shown to violate the original symmetry but to obey the generalized theorem. Nosé-Hoover dynamics are introduced as a way of understanding the content of the generalized Onsager relation. A set of extended Graham-Haken potential conditions are derived for Fokker-Planck models and shown to be consistent with the generalized Onsager relations. It is argued that realizable statistical closures with underlying Langevin representations must also obey the generalized theorem; various recent works on turbulent transport that predicted breakdown of Onsager symmetry are reconsidered in this light. Finally, a comparison is made between modern approaches to the Onsager theorem based on statistical dynamics and the original proof based on entropy production. It is shown that renormalization theory can be used to bring these various approaches into agreement, but we conclude that the dynamical approach is actually easier to apply when the steady state is turbulent.

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The Transport of Toroidal Momentum in TFTR Plasmas and Relevant Collective Modes

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It is widely known that the radial transport of momentum and energy in magnetically confined plasmas is not well-described by traditional theories relying exclusively on particle collisions. This is the case in tokamak experiments where toroidal rotation speeds up to the order of the ion sound velocity are induced by the tangential injection of neutral beams. In these experiments, the measured cross-field diffusivity of ion toroidal momentum is consistently found to exceed the predictions of traditional collisional theories by up to two orders of magnitude, ranging from 1 - 10 m^2/s [1,2].

We suggest that this transport process is associated with the excitation of plasma collective modes of the drift-type, driven unstable by gradients of the ion parallel velocity [3]. The modes we describe, although driven by gradients of the ion flow velocity, are quite different from the canonical Kelvin-Helmholtz instability, and are more easily excited under typical experimental conditions. Elements of the linear theory of these instabilities, the quasilinear theory of the transport induced by them, and related topics will be presented and discussed in the context of TFTR data. Emphasis will be placed on the evaluation of the linear growth rates under typical conditions, but special attention will be devoted to the observation that the ion thermal diffusivity χ_i and the ion toroidal momentum diffusivity χ_ϕ are similar in magnitude and appear to have similar scalings with global parameters [1]. We use this observation as a guiding criterion in selecting the appropriate mode and the relevant quasilinear theory to assess its effect on transport. We also discuss "mixing-length" criteria, which are influenced by the underlying physics of the relevant mode.

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The Reconstruction of Equilibrium in TFTR with use of EMEQ Code *

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Abstract

Due to recent progress in obtaining experimental measurements of the pitch-angle of magnetic fields in tokamaks, important information about the current distribution in the center of plasmas is now available. With additional data about the plasma pressure distribution, this information is sufficient to reconstruct the magnetic configuration in the central zone of the plasma column using the Grad-Shafranov equation. The formulation of the equilibrium problem differs from the classical formulation since the pitch-angle $i(R) = B_{pol}/B_{tor}$ as a function of the major radius (rather than the current density as a function of ψ) serves as input to the equilibrium equation.

The possibility of q-profile reconstruction when the pitch-angle $i(R)$ is known on the midplane $R_{in} < R < R_{out}$, is analized with the assumption that the shape of the magnetic surfaces is prescribed while their shift is unknown. In TFTR, pitch-angle data is obtained primarily on one side of the magnetic axis (the outboard midplane). The Electrodynamic Moment EQuilibrium (EMEQ) code has been modified to accept $p(R)$ and $i(R)$ data as input. Both interactive and conveyor modes are implemented in the code to effect the fast reconstruction of the magnetic configuration in TFTR using the direct input from the MSE and TRANSP data base.

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Differential Algebraic Plasma Simulation [1]

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Traditional methods of simulation such as Vlasov and fluid plasmas have various difficulties. One of them is the appearance of non-physical quantities such as negative density and velocity filamentation due to truncation in the simulations. One particular manifestation of this occurs in Vlasov simulation where nondissipative mixing of the phase space continuously cascades to higher powers of velocity (smaller scales). Truncation in this case leads to nonphysical filamentation of the velocity distribution.

We introduce an algorithm for these types of equations using the method of Differential Algebra. This method minimizes the effects of truncation error and opens the possibility of symbolic calculations in the compilation process for the time evolution of the equations. We assign, in place of numbers, vectors of the form: $\vec{f} = (f^{(0)}, f^{(1)}, f^{(2)}, ..., f^{(n)})$ which are time advanced with the superscipts refering to the order of derivatives n with respect to the function f. The derivatives can be carried out in any space such as ∂_v or ∂_x through the differential algebra. The time advance equation may be written in the form: $\frac{\partial \vec{\delta f}}{\partial t} = L(\vec{\delta f}, \vec{f_0})$ where $\vec{\delta f}$ is the deviation from the initial distribution, $\vec{f_0}$ is the initial distribution vector, and L is an operator. In discretized form the equation is $\vec{\delta f}_{t+1} = M(\vec{\delta f}_t, \vec{f_0})$ where M can be a map to represent Vlasov, PIC, Navier-Stokes, or any other nonlinear operator in any space such as (x, v) or (k, μ). The derivatives up to order n are carried with the function values and are updated algebraically. The advance of $f^{(n)}$ may involve terms containing $f^{(n+1)}$. The derivative truncation can be taken as a natural consequence of many mode phase mixing. The higher order derivative can also be computed by linearizing, i.e. using the exact derivative of the initial distribution f_0. Finally, the determination of the exact dervatives could also be obtained by tracking particles backwards to the initial distribution and making use of Liouville's theorem.

[1] work supported by US DOE

Energetic Particle Drive for TAE and Kinetic TAE Modes in a Low-Shear Tokamak*

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The linear power transfer from energetic particles to TAE and KTAE modes with large mode numbers is calculated in the low shear limit when each mode is localized near a single gap within an interval of a total width $\Delta = r_m/m \ll r_m$, with r_m defined by $q(r_m) = (2m+1)/2n$ where m and n are poloidal and toroidal mode numbers. Near its peak where most of the mode energy is concentrated, the mode has an inner scale Δ_{in} which is much smaller than Δ. The scale Δ_{in} is determined by toroidicity and kinetic effects which eliminate the singularity of the potential at the resonant surface.

The banana width of energetic particles Δ_b is assumed to be much larger than or comparable to the total width of the mode, in order to generalize the results obtained previously in the limit $\Delta_{in} \ll \Delta_b \ll \Delta$. It is shown that the most unstable KTAE modes are those with frequencies slightly above the gap. The power transfer from energetic particles is found to be the same for TAE and KTAE modes, which makes the growth rate proportional to the inner width of the mode.

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On the Relationship Between Marfes and Density Limits

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An analytic theory is presented describing the interrelationship between Marfes and density limits in a tokamak. It extends in several directions an earlier calculation carried out by Drake [1]. A Marfe is an asymmetric, sometimes long-lived, burst of radiation from the edge of a tokamak. Its structure usually corresponds to $m = 1, n = 0$. The density limit, often known as the Murakami limit, or the Greenwald limit, is associated with a radiation collapse of the plasma edge. The plasma undergoes an $m = 0, n = 0$ contraction, which ultimately leads to a major disruption when the minor radius has shrunk sufficiently. The first part of the theory determines the condition under which a radiation contraction occurs. Depending upon the shape of the density profile, the collapse can be either an unstable, uncontrollable transition from one meta-stable slate to another, or more desirably, a stable, controllable detached equilibrium in which 100% of the plasma energy loss is radiated away. An explicit expression is derived for the Murakami, Greenwald density limit including its dependence on auxiliary power. The second part of the theory, pertaining to the Marfe, is a classical linear stability analysis of the equilibrium described above for the radiation collapse. Here too, an explicit expression is derived determining the condition under which a Marfe occurs before or after a radiation collapse. For one class of operation, the Marfe can be used as a precursor diagnostic to predict the imminent appearance of a density limit disruption. Alternatively, it may be important to completely avoid Marfes when attempting to operate in the radiation divertor mode.

[1] J. F. Drake "'Marfes: Radiative Condensation in Tokamak Edge Plasma," Plasma Preprint UMLPF 87-020.

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Quench Protection in Superconducting Magnets

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The purpose of this obviously non-plasma physics research is to demonstrate that many of the powerful and sophisticated theoretical techniques widely used by the plasma physics community can be applied to engineering problems of direct interest to the magnetic fusion program. These problems are intellectually challenging, programmatically important, and represent new areas of opportunities for the fusion theory community as the program evolves towards ever larger engineering projects.

Quench protection is such a problem. If a sudden pulse of energy is delivered (usually by accident) to a small section of a superconducting magnet, it may go normal. Under such conditions, the magnet current flows in the surrounding copper matrix, which is essentially "in parallel" with the superconductor. Although the copper is a good conductor, it still dissipates ohmic power, further adding to the energy input. If the initial energy input is sufficiently high, the heat carried away by convection in the supercritical helium coolant and heat conduction in the copper is not adequate to restore the superconductor to its normal state. In this situation a runaway buildup of heat is generated which propagates along the length of the conductor; that is, a quench has been initiated. Practically, it is important to detect the quench as early as possible in order to shut off the current, thereby preventing irreversible damage to the conductor. This is a non-trivial problem since the cables comprising a coil can be as long as one kilometer.

The theory presented here starts with a set of multi-dimensional Navier-Stokes and heat transport equations for the coupled system of helium coolant, superconducting/copper cable, and surrounding jacket. A combination of multiple time scale expansions and asymptotic analysis reduces the problem to a nonlinear fourth order system of 1-D plus time equations. A code has been written whose numerical results are in excellent agreement with more complex engineering codes. There is at least an order of magnitude savings in CPU over the existing codes where a typical run requires one hour Cray CPU. By investigating a number of different cases we have been able to introduce further analytic approximations which reduce the problem to quasi-analytic form, a set of three ODE's in time. The results here too are in excellent agreement with the engineering code and requires only several seconds of CPU time. More important, the critical dimensionless parameters have been identified, as well as practical scaling information for the magnet design.

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Smoothing Spline Analysis of Plasma Profiles

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The plasma temperature, density and pressure profiles are analyzed statistically as a function flux radius, r, and the engineering variables, $\vec{x}^t = (q, P, \bar{n}, I_p, M)$ using smoothing splines. The smoothing parameters are determined self-consistently by minimizing an empirical estimate of the total expected error. For several smoothing parameters, we use a back projection algorithm. Local and global confidence intervals are determined. For a single measured profile, we test for local temperature gradient flattenings/magnetic islands by examining the estimated values of $\frac{\partial T}{\partial r}$. For a family of measured profiles, $Y(r_j)$, we fit an additive model:

$$Y(r, x) = Y_0(r) + Y_q(r) \ln q + Y_P(r) \ln P \ldots$$

This additive model generalizes global scaling expressions to radial functions. In our initial study of TFTR Ohmic profile database, we confirm that the profile shape variation depends primarily on the plasma safety factor.

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Calculations in the Tokamak Vacuum Region: δW_v and Diagnostic Capabilities *

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The calculational methods used for the magnetic energy, δW_v, in the vacuum region surrounding tokamak plasmas permit a natural extension to more general toroidal configurations, and also for calculating useful ancillary quantities like the simulation of the Mirnov-loop measurements, and the eddy currents generated in the conducting materials outside the plasma discharge. The generalizations include the capabilities for topologically spherical shells, and toroidally symmetric unlinked (with respect to the plasma discharge) solid conductors. The former was motivated by spheromak-like configurations, and the latter for simulating the segmented shell of PBX-M. The collocation method and Green's second identity is used for solving $\nabla^2\chi = 0$ for the magnetic scalar potential. This lends itself readily to incorporating the necessary boundary conditions, and once χ is known on the surfaces, a second application of Green's identity enables the simulation of the Mirnov-loop measurements. The eddy currents on the surface of the conductors, $\boldsymbol{K}_c$, is given by $\boldsymbol{n} \times \nabla\chi$. This is useful for visualizing the proposed coil currents needed for stabilizing the external kink modes by feedback mechanisms, and also for estimating the stresses in the shell due to disruptions, etc. The code is modular and can be easily interfaced to various stability codes like the PEST, NOVA, GATO, etc. system of codes, or can be used in a stand-alone mode for diagnostic purposes. Details of the numerical method and results will be presented. These include the efficient treatment of the singularities inherently present in the Green's function method.

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The Magnetohydrodynamic Clump Instability in Tokamaks

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The theory of magnetohydrodynamic (MHD) clump instability discussed by Tetreault (1988) predicts that a tokamak will relax into the state $\mathbf{J} = \lambda\, \mathbf{B}$ (Taylor, 1974) due to the turbulent mixing during the clump instability. While this may occur in a tokamak under extreme circumstances, as in a major disruption, it does not generally occur in well-confined tokamaks. Quasi-thermodynamic arguments have been given to obtain natural current profiles in tokamaks (Bhattacharjee, Dewar annd Monticello, 1980; Minardi, 1981; Biskamp, 1986; Hsu and Chu, 1987; Kadomtsev, 1987; Pfirsch and Pohl, 1987; Taylor, 1990), but none of these arguments have been rigorously connected with MHD dynamics. Of all the cited models, Taylor's (1990) comes closest to the clump model of Tetreault (1988), but the final state in Taylor's and Tetreault's calculations are quite different. It is this interesting discrepancy that stimulated us to revisit Tetreault's dynamical calculation.

We derive the two-point renormalization equations for resistive MHD, following the prescriptions of clump theory (Boutros-Ghali and Dupree, 1981). Our strategy for calculating relaxed states using the renormalized equations is different from Tetreault's. Tetreault calculates the clump growth rate from the renormalized equations, and then deduces the relaxed current profile in a somewhat ad hoc manner from the requirement of zero growth rate. We calculate the current profile by solving the mean-field Ohm's law in which we incorporate the fluctuation amplitude given by the two-point renormalized equation. The magnitude of the clump-strength determines two qualitatively different classes of solution : the Taylor state, representative of relaxed reversed-field-pinches, and the tokamak current profile which exhibits strong gradients in the current profile.

Numerical Models of Weather and Climate

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Numerical weather prediction has provided routine forecasts of global weather for more than thirty years. During that period numerical models have evolved from the use of low resolution balance equations to high resolution fluid dynamics equations with added terms to describe physical processes such as radiative heating and latent heat release. Both grid-point and spectral-transform methods have been used. Forecasts require an initial state, and much effort has gone into data assimilation and initialization consistent with the nonlinear dynamics of the models. As is well known, the chaotic atmosphere is of limited predictability, and deterministic weather forecasts are only good for about a week.

The climate is defined by the statistical properties of the weather, and these change far more slowly. There is much current interest in the response of the climate to human influences. Global climate change studies are largely based on weather models of lower resolution that are run for much longer times and averaged. But the search continues for a true climate model that deals directly with slowly evolving statistics.

DESTABILIZATION OF THE INTERNAL KINK BY ENERGETIC-CIRCULATING IONS

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ABSTRACT

A stability analisys is carried out for the $m = 1$ internal kink mode, in the presence of energetic-circulating particles. It is found that, including the effect of finite radial particle-orbit excursion, the $m = 1$ internal kink mode is strongly destabilized by the resonant interaction with the energetic passing particles. Such an instability could explain the experimental observations of the "fishbone" oscillations during tangential neutral beam injection[1,2]

1 W.W. Heidbrink *et al.*, Phys. Rev. Lett. 57, 835 (1986)

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Tight Aspect-Ratio Tokamaks: Theory and Experiment

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The START (Small Tight Aspect Ratio Tokamak) experiment became operational at Culham in January 1991, obtaining hot, high density plasmas at aspect ratios $A(=R/a) \sim 1.35$ [1]. Results from START provide the first experimental evidence of the significant changes predicted to occur in low aspect ratio plasmas [2].

Experimental results will be compared with theoretical modelling in the areas of:

equilibrium: demonstrating high natural elongation and D-shaping at low A, together with evidence of neo-classical and bootstrap effects;

confinement: comparison with common scaling laws shows that τ_E exceeds the neo-Alcator scaling and is better represented by the Rebut-Lallia and Lackner-Gottardi models;

stability: START plasmas have good positional stability without need of feedback control, although the vacuum wall is far removed from the plasma; and the major disruption appears to be absent whilst $A < 1.8$.

These properties encourage further study, both theoretical and experimental, of low aspect ratio tokamaks.

Acknowledgements

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INFLUENCE OF LOCAL DENSITY AND TEMPERATURE GRADIENTS ON INTERNAL MODES IN HIGH TEMPERATURE PLASMAS*

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We have considered internal $m = n = 1$ modes associated with the crash phase of sawtooth oscillations in plasmas in high temperature regimes. The mode equations in the 'reconnection layer' about the $q(r_s) = 1$ singular surface for the collisionless ions and the collisional electrons are reduced to a single integro-differential equation in both real and Fourier transform space. By using a two-point Padè approximant to simplify the parallel electron response, a second order, homogeneous differential equation is obtained in Fourier transform space. This equation, written in terms of the parallel current $\overline{J}(k)$, retains the full ion perpendicular dynamics to all orders in the ion Larmor radius. For a numerical solution, however, it is convenient to use the radial component of the electric field $\overline{E}_r(k)$ as dependent variable[1], as the matching condition with the external, ideal-MHD solution is in this case very simple, $\overline{E}_r(k \to 0) \sim const.(1 - \lambda_H k sgn k)$ (here λ_H is the ideal-MHD stability parameter[2]).

We have solved the $\overline{E}_r$-equation numerically for a broad range of plasma parameters, focussing in particular on the influence upon the mode growth rate of the local density and temperature gradients associated with the electron drift-wave and ion diamagnetic frequencies.

While the influence of the density gradient scale length $L_n \equiv (-d\ln n/dr)^{-1} |_{r=r_s}$ is always stabilizing leading to a reduction of the mode growth rate as L_s/L_n is increased (peaking of the density profile and/or increasing of the magnetic shear length L_s), the influence of the temperature gradient scale length $L_{Tj} \equiv (-d\ln T_j/dr)^{-1} |_{r=r_s}$ is more complicated.

In particular, we find that, in the case of an ideal-MHD unstable plasma equilibrium ($\lambda_H > 0$) and for large ion Larmor radius, the mode growth rate is not a monotonically decreasing function of L_s/L_n if $\eta_i = L_n/L_{Ti} > \eta_i^{crit} \simeq 1.6$. In this case the growth rate, while at first diminishing with L_s/L_n, suddently increases as L_s/L_n crosses a threshold value and then becomes nearly independent of L_s/L_n. This behavior, that can be interpreted as the appearance of a new root with a significant growth rate in the eigenvalue equation , was first observed in Ref.[3] by analytically solving the relevant mode equation.

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A Comparison of the Performance of a Fluid Code on the C90 and the iPSC/860*

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The performance of nonlinear runs of a fluid code on the NERSC C90 and the ORNL Intel iPSC/860 will be compared. This version of the KITE code is an initial value, three-dimensional, nonlinear, five-field code used for plasma turbulence studies. Because of the Fourier harmonic expansions in both sines and cosines, it has ten equations. The runs have from 385 to 513 radial grid points and 455 to 539 Fourier harmonics. The main components of the code are convolutions of Fourier harmonics and block tridiagonal matrix solves. Both parallel codes are optimized for the computer they use.

With the collaboration of NERSC, microtasking calls have been added to the KITE serial code on the C90. The loop that contains calls to the block tridiagonal matrix solver is performed in parallel over the number of Fourier harmonics. The convolution routines also contain microtasking commands to compute the do loops in parallel over the number of Fourier harmonics. We are using an average of six concurrent CPUs for runs of thousands of timesteps in batch and many of the subroutines called every timestep are not microtasked yet.

The KITE parallel code is running on 128 processors of the iPSC/860. 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.

We will compare CPU times, constraints imposed by memory size of the machines, difficulties in storing resulting data, and wallclock time needed to complete nonlinear runs.

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ABSTRACT
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Fluid Equations for Plasmas with a Strong Radial Electric Field and Steady Flow*

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Studies of a tokamak plasma with a strong radial electric field and large mass flows have recently been attracting significant amount of interest, in relation to the H-mode phenomena. Topics of investigation in the literature include bifurcation or spontaneous spin-up of plasma equilibrium into a large poloidal rotation state, shear stabilization of plasma turbulence, anomalous stress forces, etc. One of the difficulties in this subject has been the lack of fundamental plasma equations relevant to strong radial electric field and large mass rotation, upon which these anomalous or boundary effects can be built.

In this report, we present fundamental plasma equilibrium equations with large radial electric field and mass flow. Anomalous forces due to, e.g., turbulence or orbit-loss effects are considered as an additional unknown term. New viscosity coefficient, additional flux-surface shift effect, and the generation of poloidal density asymmetry due to large mass flow have been studied. It is found that all these effects can play important roles in the determination of force balance relations, and these physics should be included in the study of H-mode physics. A simple analytic expression for the plasma viscosity at general flow velocity is also presented.

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Effects of Flux Surface Jitter on Electrostatic Drift Waves*

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An investigation is made into the possibility of stabilizing electrostatic drift waves by oscillating, or "jittering," a rational flux surface about its equilibrium position. Previous studies[1,2] of the jitter stabilization of linear tearing modes in the context of reduced MHD encourage and underlie the present work since drift waves, like tearing modes, are localized about rational flux surfaces. A simple fluid model[3] which combines the electrostatic drift wave physics of the Charney-Hasegawa-Mima equation with reduced MHD furnishes an elementary context for the present study.

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Nonlinear Gyrofluid Simulations of Toroidal ITG Turbulence

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We present nonlinear simulations of ITG turbulence in toroidal geometry using a gyrofluid model including the effects of parallel resonances, toroidal drift resonances, and FLR effects.[1] The linear eigenfunctions and frequencies from this model agree with fully kinetic numerical calculations.[2]

Our simulation uses a field-line coordinate system which efficiently represents turbulence for high mode numbers, where the perpendicular correlation lengths are much shorter than in the parallel direction. It is very similar to the ballooning representation, although we have incorporated periodicity constraints in a way which allows the $\mathbf{E} \times \mathbf{B}$ nonlinearity to be evaluated with FFTs. In these coordinates it is easy to implement periodic radial boundary conditions which allow the ($m = 0$, $n = 0$) components of fluctuations (including self-generated poloidal flows) to vary self consistently while maintaining fixed average background gradients.

Nonlinearly, we find that with the proper adiabatic electron response, $n_e/n_0 = e(\Phi - \langle\Phi\rangle)/T_e$, where $\langle \ldots \rangle$ is a flux surface average, a sheared poloidal rotation is generated which in turn damps the unstable modes, and the steady state is determined by the competition between the nonlinear generation of sheared flow, and damping of the turbulence by this flow.

When the traditional adiabatic electron response is used, $n_e/n_0 = e\Phi/T_e$, (which might be justified in the presence of stochastic magnetic fields which allow radial electron flow) the sheared flow is suppressed. Energy from the fastest growing modes is driven to long wavelength, eventually going to the longest wavelength in the system, which grows indefinitely.

The generation of poloidal flow and subsequent reduction in fluctuation levels is similar to that observed in simulations by Hasegawa and Wakatani[3] for resistive drift waves and by Carreras *et al.*[4] for resistive pressure gradient driven turbulence, and predicted to play an important role in generating L to H-mode transitions by Diamond and Kim[5].

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A Moving Finite Element Model of the Tokamak Scrapeoff Region

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The scrapeoff region of a tokamak, associated with the poloidal divertor and collector plates, has been a subject of intense recent interest because it is responsible for handling a major portion of the heat load from the fusion reactions and must survive great stresses. Detailed fluid modeling has been done to optimize the design of this region, with the expectation that it is a crucial component of a practical tokamak reactor. Severe numerical problems are caused by extreme anisotropy of the plasma transport, the presence of a magnetic x-point inside the computational domain, thin boundary layers at the collector plates, and multiple time scales associated with Alfvén and sound waves.

The principal approach to these difficulties has been to map the complex spatial domain to a rectangular domain in orthogonal flux coordinates, which can then be gridded finely where needed, using a piecewise uniform rectangular grid, assuming a given, time-independent magnetic field. This approach suffers from several problems. The flux coordinate system has a singularity in the neighborhood of the x-point, requiring special ad-hoc treatment. The use of orthogonal coordinates makes it difficult to handle collector plates which are not orthogonal to the magnetic field lines, as is desirable for engineering considerations. Packing the grid in regions of narrow boundary layers, such as the neighborhood of the plates, requires human intervention and guesswork. There is no simple way to adapt this approach to time-dependent magnetic fields.

We present a new approach based on the use of Moving Finite Elements and Graph Massage. We use an unstructured grid of triangles, providing great flexibility in fitting the complex domain in the original cylindrical coordinates. The grid automatically and dynamically adapts to the evolving solution with no reliance on the coordinate system, naturally approximating a flux coordinate system where the poloidal field is strong while relaxing to a more isotropic distribution in the neighborhood of the x-point. The elimination of the flux coordinate transformation simplifies the fluid equations, avoids the singularity at the x-point and the problem of non-orthogonal collector plates, and allows for the treatment of time-dependent magnetic fields. The adaptivity of the grid automatically refines the resolution near the plates with no human intervention. A fully implicit time step allows for efficient treatment of the multiple time scales.

Due to the exclusion of the core, the computational domain is multiply-connected with curvilinear boundaries. The Graph Massage algorithm, whose primary role is in enhancing grid adaptivity for the evolving solution, plays a role as well in the non-trivial task of initially gridding up our computational domain.

Results will be illustrated with 3D color movies showing the evolution of the grid and the solution.

A Moving Finite Element Model of The Incompressible Kelvin-Helmholtz Instability

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The Kelvin-Helmholtz instability, caused by the sheared flow of fluids and plasmas, is of considerable practical importance in many applications. It may play a role in the edge turbulence associated with anomalous transport in the scrapeoff layer of tokamaks.

Many features of this problem cause it to be one of the classic challenges to Computational Fluid Dynamics (CFD). The interesting behavior is localized to a narrow shear layer. For large Reynolds numbers, turbulence develops in this region, with thin ribbons of fluid interacting locally. In the incompressible limit, Poisson's equation must be solved for the stream function, along with the equation for convection of vorticity. Attempts to deal with the problem with adaptive and Lagrangian grids have a tendency to fail because the sheared flow can tear the grid apart.

We treat the incompressible Kelvin-Helmholtz instability primarily as an interesting challenge in our development of the methods of Moving Finite Elements and Graph Massage as a general-purpose technique for difficult 2D problems in CFD. Moving Finite Elements provides a continuously adaptive motion of the unstructured triangular grid, concentrating it in regions of sharp gradients associated with the shear layer and the thin ribbons. Graph Massage allows the grid to break and reconnect occasionally, giving it the topological flexibilty to avoid tangling. Periodic boundary conditions avoid interference of the boundaries with the flow, and Graph Massage allows us to take portions of the grid which flow out one side and put them back on the other side. The results now appear robust and believable. Our 3D color movie shows vortices developing, merging, and circulating. The grid surges and boils around with the vortices with no difficulty. Vorticity is conserved to about 1 part in 1000 for the duration of a long run at a Reynolds number of 1000, with nonconservation of vorticity due primarily to Graph Massage rather than Moving Finite elements.

One interesting conclusion is that the time-asymptotic behavior of the solution varies with the length of the domain in the direction of the flow. We initialize the perturbation with the most unstable linear eigenfunction and choose the periodicity length to be an integral number of wavelengths of this mode. With one wavelength, vortices develop and merge, broaden the shear layer, and then fade away, leaving a broadened layer which is stable to all modes which fit into the domain. With two wavelengths, a single large vortex eventually forms and persists for as long as we let it run.

The expense of increasing the domain size goes up rapidly because we use a direct envelope method for solving our large, sparse, linear systems. This is a problem for any application with a large grid and many dependent variables. We are therefore developing a new iterative matrix solution procedure using buffered relaxation with Krylov acceleration. Results of this iterative method will be presented.

Nonlinear Gyrofluid Models of Shear Alfvén Instabilities in Ignited and Beam Heated Toroidal Plasmas*

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The gyrofluid model with Landau closure[1] has proven to be a powerful technique for analyzing shear Alfvén instabilities driven by energetic populations. This approach leads to a set of coupled fluid time evolution equations which may be solved using an initial value code (TAE/FL). A variety of damping mechanisms which are relevant to the TAE (Toroidal Alfvén Eigenmode) instability such as ion and electron Landau damping, ion FLR, and continuum damping can readily be included in such equations. It is feasible to include an adequate Fourier mode spectrum and radial resolution to treat many cases of interest both linearly and nonlinearly. This model has now been applied to a range of tokamak devices such as TFTR, DIII-D, ITER as well as more recently to stellarators such as W7-AS and ATF where both TAE and GAE (Global Alfvén Eigenmode) can be present. A number of systematic trends emerge from these different cases and will be discussed. For example, as noncircular shaping increases, either through higher beta or external coils, the TAE mode spectrum becomes richer and generally shifts to higher toroidal mode numbers. Due to greater sideband coupling, the TAE instability threshold can shift to lower values of v_{hot}/v_A than for simple low beta, circular cases; also, ion Landau damping becomes increasingly important. Another observed trend is that with decreasing shear, the location of the TAE root moves towards the outer edge of the plasma and eventually becomes inaccessible. The GAE mode can then become the dominant instability and can have a very low beta threshold and high growth rate. Nonlinear saturation mechanisms within the gyrofluid model will also be discussed. One source for these is through the generation of $n = 0$ components from nonlinear beatings of $n > 0$ modes. Both $m = 0$ (equilibrium profile modification) terms as well as $m > 0$ components are retained in all dynamical variables. Finally, a new form of the gyrofluid equations which retains the velocity dependence of the energetic species drift velocity will be discussed.

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A Fokker-Planck Equation for Moderately Coupled Plasmas

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Abstract

A Fokker-Planck equation has been generalized to treat large-angle as well as small-angle binary collisions in plasmas. For moderately coupled plasmas ($1 \lesssim$ Coulomb logarithm ($ln\Lambda_b$) $\lesssim 10$), preliminary calculations have been made of the relaxation rates and transport coefficients. In general they differ from the standard (Braginskii) results by terms of order $1/ln\Lambda_b$. Using this modified collision operator, a new vector potential that has a direct and practical connection to the Rosenbluth potentials is obtained. In addition, we calculate a reduced electron-ion collision operator that, for the first time, manifests the $1/ln\Lambda_b$ corrections.

Radial Electric Field Influence on the Neoclassical Orbits in Tokamaks.

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The analysis of the neoclassical orbits in the presence of the steep electrostatic potential typical for tokamak edge is performed. Standard approach implying (i) the series expansion of electrostatic potential, Φ, and (ii) independence of particle trajectories on the radial electric field, E_r, is valid only in the limited parameter range. In particular, for the parabolic profile strong influence of electrostatic potential on neoclassical trajectories was expected for $S \gg 1$ ($S=|1+(e/m)\omega_p^{-2}d^2\Phi/dr^2|$, $\omega_p=eB_p/mc$ - poloidal Larmor frequency) resulting in the squeezing of banana orbits by a factor $S^{1/2}$. But at $S \geq 1/4\varepsilon$ this result is valid only in the vicinity of the potential extremum of the order of one banana orbit size $\delta r_b \approx \rho_p(\varepsilon/S)^{1/2}$, $\rho_p=v_o/\omega_p$ - the poloidal Larmor radius. Outside this region all the trajectories becomes passing and are squeezed stronger. The characteristic orbit width is inversely proportional to E_r: $\delta r_p \approx 2\varepsilon\rho_p/|v_E|$, $v_E=cE_r/B_p$. For the arbitrary potential profile there two condition of applicability of the standard approach, $v_E \ll v_o$ and $\delta r \ll L_\phi$, L_ϕ - characteristic scale length of the electrostatic potential. Roughly these inequalities can be rewritten as follows $\rho_p/L_\phi \ll W/e\Phi \ll 1/\varepsilon$. For the conditions of tokamak plasma edge the applicability region of standard approach in relatively narrow. Therefore either left or right inequality are violated resulting in more complicated dependence of neoclassical trajectories on electrostatic potential. In the region of high electric field trajectories of low energy particles, $W \ll e\Phi$, are squeezed stronger than it was expected. Trajectories of higher energy particles, $W \geq e\Phi$, can be either squeezed or expanded depending on the whole profile $\Phi(r)$. The influence of the electrostatic potential profiles similar to that can emerge at plasma periphery on ion prompt losses is studied numerically. We found that positive step-like potential located at $\approx 1.5\rho_p$ from the separatrix increases ion prompt losses. Ion losses in turn increase the amplitude of the potential. Combined these two processes can destabilize potential profile and strongly contribute to the fast formation of electrostatic barrier during L-H transition.

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Symmetry Groups and Solutions of Plasma Fluid Models*

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From the general group of Lie point symmetries admitted by a system of p.d.e.'s (obtained by computer algebra), we seek reductions of the number of independent variables leading to systems of nonlinear o.d.e.'s. These equations can be solved in particular cases yielding exact analytical solutions (similarity solutions) for the original p.d.e. This general Lie group analysis has been applied to low-β reduced MHD, for which a detailed discussion of solutions is given. Due to the general nature of this procedure, the study of a family of more complicated fluid models can be pursued.

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Ideal MHD analysis of advanced regime tokamaks

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Interest in steady-state tokamaks has extended the regime in parameter space into new areas where conventional methods of determining ideal MHD stability are experiencing difficulties. For instance, a major area of interest is the high $\beta_{\rm pol} \approx R/a$ regime, where the bootstrap fraction can approach unity. This is usually achieved when $q_{\rm edge}$ becomes large (≈ 15). At these values $q'_{\rm edge}$ also becomes very large. It is observed that at these limits stability analysis becomes more difficult and careful convergence studies are required. We have addressed this issue for a sequence of equilibria where $q_{\rm edge}$ varies from 10 to 35 and $\Psi q'_{\rm edge}$ varies between 100 and 1000. We will present the results of convergence studies using the PEST [1] and ERATO [2] codes.

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FUEL AND HELIUM CONFINEMENT IN FUSION REACTORS*

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An expanded macroscopic model for particle confinement is used to investigate both fuel and helium confinement in reactor plasmas. We illustrate the relative effects of external sources of fuel, divertor pumping, and wall and divertory recycle on core, edge and scrape-off layer densities by using separate particle confinement times for 'core' fueling (deep pellet or beam penetration, τ_c), 'shallow' fueling (shallow pellet penetration or neutral atoms that penetrate the scape-off layer, τ_s) and fueling in the scrape-off layer (τ_{sol}). Because τ_s is determined by the parallel flow velocity and characteristic distance to the divertor plate, it can be orders of magnitude lower than either τ_c or τ_{sol}. A dense scrape-off region, desirable for reduced divertor erosion, leads to a high fraction of the recycled neutrals being ionized in the scrape-off region and poor core fueling efficiency. The overall fueling efficiency can then be dramatically improved with either shallow or deep auxillary fueling. Helium recycle is nearly always coupled to the scape-off region and does not lead to strong core accumulation unless the helium pumping efficiency is much less than the fuel pumping efficiency, or the plasma preferentially retains helium over hydrogenic ions. Differences between the results of this model, single-τ_p macroscopic models, and 1-D and 2-D models are discussed in terms of assumptions and boundary conditions.

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Neoclassical Tearing Dynamo and Self-Sustainment of a Bootstrapped Tokamak

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It has been suggested by Boozer (1986) that a completely bootstrapped tokamak which requires no seed current is possible due to the "dynamo effect" caused by tearing modes (Boozer, 1986; Bhattacharjee and Hameiri, 1986; Strauss, 1986). The tearing instabilities are expected to generate poloidal flux spontaneously near the axis, thereby dispensing with the need for an external seed. Numerical calculations have been carried out by Weening and Boozer (1992) confirming the feasibility of a completely bootstrapped tokamak. These calculations use the resistive MHD model, with the pressure profile held arbitrarily fixed. Several questions naturally arise. Is resistive MHD a good model in the low-collisionality regime of present-day tokamaks in which large bootstrap currents have been observed? Is it consistent to rely on pressure gradients to provide the bootstrap current, but then omit pressure gradients in investigating the tearing instabilities that provide the dynamo effect? And how realistic is it to assume that a strong pressure gradient is sustainable in the central region where current relaxation is expected to produce a dynamo effect?

In this paper, we investigate the dynamo effect in a bootstrapped tokamak within the framework of the neoclassical MHD model (Callen and Shaing, 1985; Connor and Chen, 1985; Hahm, 1988; Fitzpatrick, 1990; Yang et al., 1992) which is more realistic than resistive MHD for the regime in question.Since neoclassical MHD includes trapped-particle effects, it can, in principle, provide an additional mechanism for exciting tearing modes which are known to be stabilized by temperature gradients. We investigate the properties of the dynamo field ε, and find that the original definition $\varepsilon = \langle \mathbf{v}_1 \times \mathbf{b}_1 \rangle$ used in incompressible resistive MHD is no longer adequate; neoclassical MHD forces a redefinition of ε due to the requirements imposed by the helicity conservation constraint. This redefinition is a physical consequence of the force-flux relation in an unstable plasma with pressure fluctuations. We calculate the new parallel dynamo field from first principles using the boundary-layer equations governing neoclassical tearing instabilities, including the effect of pressure fluctuations. With the derived form for ε, we obtain steady-state current profiles. These profiles have a relaxed core region of weak pressure gradients surrounded by a region of strong pressure-gradients where bootstrap currents dominate. Thus a completely steady-state bootstrapped tokamak sustained by a neoclassical tearing dynamo is realizable. However, we are pessimistic that such a tokamak, even if it were resistively stable, would be stable to ideal kink modes.

Unification of Fully Implicit Fluid Edge-Plasma Transport Codes*

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We are developing a modular 2-D edge-plasma transport code that incorporates pieces from three existing fully implicit codes: LEDGE, NEWEDGE, and NEWT-1D. The modularity allows the users to choose from different physics models and numerical algorithms, and allows new models to be introduced in a straightforward manner. The new code is named UEDGE. The physical model of the plasma is given by the Braginskii equations with the addition of anomalous transport across the magnetic field lines. Plasma currents and cross-field $\boldsymbol{E} \times \boldsymbol{B}$ and diamagnetic drifts have been added. The code is written for multi-species to include various charge states of impurities, but initially will contain an average-ion description for the impurities. The neutral gas model contains two species, a charge-exchange group and a Franck-Condon group. The atomic physics data for ionization, charge-exchange, and radiation come from ADPAK.[1]

The use of a fully-implicit method requires calculating the Jacobian matrix, which can then be solved by direct or iterative methods. As the solution of the matrix typically takes the majority of the computer time, we will present a timing comparison between a direct Newton method, an iterative Newton method, a preconditioned Krylov Newton method, and time-dependent schemes. The overall structure of the code will be described together with a set of sample problems.

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Stability Threshold of TAE Modes*

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We present new results of a global calculation of linear stability threshold of toroidal Alfven eigenmode (TAE) destabilized by energetic particles in tokamak plasmas including the effects of finite orbit width of energetic particles and the collisional damping of trapped electrons, in addition to electron and ion Landau dampings. These kinetic effects are calculated fo numerical tokamak equilibria at finite plasma beta, without the usual low beta, large aspect ratio approximations. The effects of finite drift orbit width are retained by solving the drift kinetic equation in the toroidal angular momentum space. The electron collisional damping is calculated by solving numerically the bounce-averaged drift kinetic equation for trapped electrons, including the pitch angle collision operator and the perturbed parallel electric field. Thus, our results are valid for arbitrary electron collisoň frequency and general equilibrium.

We have calculated the critical fast particle beta for TAE instability for a wide range of parameters. The calculated thresholds are found to be in good agreement with the experimental observations in TFTR[1-3]. First, in the TFTR NBI experiments[1], the low-n TAE modes were observed to be excited by tangentially injected fast beam particles (i.e., circulating partilces) at low toroidal field of B=1T. For this case, we find that the finite orbit width effects enhance the destabilizing contribution of fast particles for the n=2 and n=3 modes. The dominating damping mechanisms are electron collisional damping and the ion Landau damping. Second, in the TFTR ICRF-heating experiments[2], the TAE modes were observed to be destabilized by the fast trapped ions produced by ICRF-heating at toroidal field of B=3.26 T. For the parameters of this experiment, we find that the finite orbit width effects reduce the fast particle destabilizing contribution. The collisional damping of trapped electrons is found to be the dominating damping mechanism. Finally, we present the stability calculation of TAE modes in the proposed TFTR D-T experiments[3].

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Fast Ion Physics Related to Cyclotron Emission*

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Collective stability of fusion produced fast ions and its effect on confinement are the intellectually most challenging as well as programmatically most important issues of burning plasma physics. By including an energy dependence on the cyclotron frequency of fast and slow ions, we reveal a novel concept, a two-stream in gyrospace even without beams in real space. This leads to a two-energy-stream cyclotron instability for fast ions to drive waves and to slow down anomalously. The instability comes from the coupling of the fast and slow ion Bernstein branches. The growth rate of the cubic instability is proportional to $(n_f / n_s)^{1/3} (\gamma_f - 1)^{1/3}$ while the efficiency $\propto (n_f / n_s)^{1/3} (\gamma_f - 1)^{-2/3}$, where n is the density and γ is the Lorentz factor. The first proton harmonic in a D-D plasma belongs to the cubic instability while the first alpha harmonic in a D-T plasma becomes a coupled quadratic instability, which is much weaker. A quadratic instability with growth rate $\propto (n_f / n_s)^{1/2}$ dominates at high harmonics. Both linear and nonlinear scaling laws have been verified by our full kinetic particle-in-cell simulation with quiet start. The theoretic and simulation studies achieved good agreement with measurements of ion cyclotron emission in D-D and D-T experiments on JET. The simulation results also show that the fast ions are anomalously slowed down while some of them are accelerated to twice of their birth energy, the fast ion density fluctuation and the phase space bunching are large, and the background ions are heated up and become non-Maxwellian.

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Kinetic simulation of η_i modes and transport in tokamaks*

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The Toroidal Particle Code (TPC) is used to examine η_i modes and transport in a toroidal plasma. Kinetic ion and adiabatic electron responses in a toroidal metric were used. Simulations involving both multiple and single toroidal Fourier modes were performed.

The measured ion heat diffusivity χ_i from our simulations is of similar magnitude and radial variation as that seen in tokamak experiments. The multiple toroidal mode runs show behavior similar to the single toroidal mode runs, establishing the primary importance of toroidicity-induced coupling of rational surfaces through the poloidal mode number over any toroidal mode coupling. In all runs the presence of a global mode, together with the formation of radially extended "streamers" which decrease in extent after saturation suggests a possible mechanism for transport.

The temperature profile follows a slow self-similar relaxation as it approaches marginal stability, but maintains the instability that drives the steady state heat flux. This state is a self-organized critical state, with any change in local temperature causing a change in the wave activity and transport, resulting in a globally smooth temperature profile. This behavior yields a radially increasing χ_i. The size of the observed "streamers" in our simulations suggests Bohm scaling.

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Poloidal Flow Generation in the Evolution of Trapped Electron Drift Instabilities in the Collisionless and Semicollisional Regime

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Experimental observations of a strong shear flow layer in the edge plasmas of tokamaks[1] and transport studies in DIII-D[2] showing a sharp increase in the poloidal flow coincident or preceding the change in thermal confinement properties (L-H transition) motivate us to consider self-consistent mechanisms for generation of poloidal flows. We consider intrinsic mechanisms for the formation of shear flow boundary layers and in particular we focus on the drift wave fluctuation-based mechanisms. The generation of mean poloidal flows has been previously observed in numerical simulations of resistive pressure-gradient-driven turbulence[3].

In a previous three dimensional gyrokinetic particle simulation of the collisionless trapped electron drift instability[4], a mean poloidal flow was observed but the simulations were on too short of a time scale to observe the effects of the shear flow on the fluctuations. More careful diagnostic analysis of the simulation and longer simulation time scales has revealed two interesting results. First, we have found that the poloidal flow generation was influenced by the position of radial drift wave eigenmodes, localized by magnetic shear. with respect to the limiter in the simulation region. When the eigenmodes interacted with the limiter, the broken symmetry of the radial drift wave propagation induced a poloidal flow in the manner discussed by Diamond et al.[5] Second, we have found that over longer time scales this poloidal flow reduced the fluctuation level and hence the particle and heat transport. The results of simulations and comparisons with previous theoretical analysis as well as poloidal flow damping mechanisms will be discussed.

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Neoclassical Rotation of Impure Plasma in Tokamaks

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The rotation of impure plasma in neoclassical regions is investigated. The rates of relaxation to steady-state rotation are determined in plateau and banana regions. Both cases of subsonic and supersonic parallel motion of impurities are considered. The steady state poloidal velocity of impurities usually is in the same direction as the primary ions in plateau region, but in the opposite direction in banana region. The supersonic parallel rotation of the impurities can modify the poloidal rotation of the primary ions.

Divertor Design Study Using LEDGE and DEGAS *

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We have used the multispecies fluid simulation code LEDGE and Monte Carlo neutral transport code DEGAS to study various divertor designs applicable to TPX and DIII-D, with the objective of optimizing the configuration with respect to radiative loss and backflow of particles to the plasma core. After the two-fluid neutrals model currently implemented in LEDGE was benchmarked by comparing its predictions for the neutral and ionization-source densities with those of DEGAS for a simple slot geometry, a fixed plasma generated by LEDGE was used as a target for several DEGAS runs. The plasma grid was large enough to include various internal DEGAS boundaries intended to simulate a variety of divertor configurations: 1) rectangular slot; 2) box, i.e., a slot with baffles perpendicular to poloidal field lines upstream from the divertor plate; 3) "venetian blinds", a series of perpendicular baffles parallel to one another. Our approach attempts to take advantage of the ability of the Monte Carlo technique to deal with complicated geometries and the relative speed of fluid simulations without a full-scale iterative coupling of the two, and should give at least a qualitative measure of the relative merits of the different designs.

We have also performed gas-target simulations with LEDGE for the divertor region of an ITER geometry using gas injection from the side walls near the divertor plate. We observe that even though temperature reduction can be accomplished, most of the power still flows to the plate.

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Lower Hybrid Current Drive in Shaped Tokamaks

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A time dependent lower hybrid current drive tokamak simulation code has been developed. This code combines the BALDUR tokamak simulation code and the Bonoli/Englade lower hybrid current drive code [1] and permits the study of the interaction of lower hybrid current drive with neutral beam heating in shaped cross-section plasmas. The code is time dependent and includes the beam driven and bootstrap currents in addition to the current driven by the lower hybrid system. Examples of simulations are shown for the PBX-M experiment which include the effect of cross section shaping on current drive, ballooning mode stabilization by current profile control and sawtooth stabilization.

A critical question in current drive calculations is the radial transport of the energetic electrons. We have developed a response function technique to calculate radial transport in the presence of an electric field. The consequences of the combined influences of radial diffusion and electric field acceleration are discussed.

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Anomalous Sources of Radial Electric Fields in Tokamaks

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Recent experiments[1] have supported several neoclassical predictions regarding tokamak rotation. However, a central figure in these comparisons is the radial electric field, $E_{0,r}$, which is generally taken empirically. Neoclassical theory does not give an accurate prediction of $E_{0,r}$, which is often thought to be determined by turbulent transport. However, the mechanisms by which turbulence affects $E_{0,r}$ are not well understood.

This work examines the turbulent correlation functions (quasilinear or nonlinear) which affect $E_{0,r}$. There are at least three ingredients necessary for such a study: 1.) rotation, which is directly related to $E_{r,0}$ via the $E \times B$ drift, and the two cannot be considered independently, 2.) toroidicity, since magnetic pumping[2] has a strong influence on plasma rotation, and therefore on $E_{0,r}$, and 3.) fluctuations, since classical and neoclassical theories have failed to account for angular momentum transport. While any two of these may have been considered together, there apparently has been no consistent theory with all three included.

We consider a general axisymmetric tokamak configuration, with two-fluid electrostatic equations and drift-wave-order fluctuations. The following turbulent correlations are found to affect $E_{r,0}$.

1. *Angular momentum diffusivity:* This is a turbulent diffusive term acting on the vertical angular momentum, $\mathbf{R} \times \mathbf{V}_\phi$. It is analogous to the momentum diffusivity found in a previous study,[3] but here fully toroidal. Surprisingly, it is not the shear flow that drives relaxation, but rather the gradient of angular momentum.
2. *Parallel Reynolds stress:* This is proportional to $\langle \widetilde{v}_r \widetilde{v}_\parallel \rangle$, where $\langle \ldots \rangle$ denotes an ensemble average.
3. *Perpendicular Reynolds stress:* This is proportional to $\langle \widetilde{v}_r \widetilde{v}_p \rangle$, where $\widetilde{v}_p$ is the prependicular turbulent velocity on the flux surface.
4. *Coriolis Reynolds stress:* This arises from a Coriolis force in a rotating plasma, and apparently has not been considered previously in a tokamak.

The first of these terms is diffusive, and acts to relax $E_{r,0}$. The last three are "off-diagonal" terms, and any of them can act to generate $E_{r,0}$. Rough comparisons for drift wave frequencies and wavelengths show that they have comparable magnitudes. Each drive of $E_{0,r}$ requires some spectral asymmetry, in order to supply the angular momentum pseudovector.

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Edge Turbulence from the Tokamak Core

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It is well known that the tokamak edge plasma is strongly turbulent, but the source of the turbulence is unknown. Various instabilities have been considered, but no known driving mechanism is strong enough to account for the large amplitudes observed. However. the focus has generally been on instabilities that are *local* to the edge plasma.

In this work, we consider the possibility that edge turbulence originates as core fluctuations which propagate radially outward. This scenario has not been previously considered seriously, assumedly because core fluctuations are "small amplitude," $\langle \widetilde{n}/n_0 \rangle_{\rm rms} \ll O(1)$, with too low a level to drive the "large amplitude," edge fluctuations, which have $\langle \widetilde{n}/n_0 \rangle_{\rm rms} \sim O(1)$. Upon closer inspection, this argument may be mistaken, since experimental observations suggest that the increase of $\langle \widetilde{n}/n_0 \rangle_{\rm rms}$ may come more from the decrease of n_0 at the plasma edge, while $\langle \widetilde{n} \rangle_{\rm rms}$ stays roughly constant. Of course, wave energy is related more to $\widetilde{n}$ than to $\widetilde{n}/n_0$, so this observation suggests that no local energy source may be required to explain edge fluctuation levels. Similar arguments apply to field fluctuations, $e\widetilde{\phi}/T_e$.

Our tokamak edge scenario is analogous to oceanic surface waves washing up on the shore. Density, n, corresponds to $h = h_0 + \widetilde{h}$, the height of the ocean surface above the ocean floor. In deep parts of the ocean (corresponding to the core), surface waves have $\widetilde{h}/h_0 \ll 1$. As the waves approach the shore (*i.e.*, the edge plasma), $\widetilde{h}/h_0$ increases dramatically, not from any energy source, but rather from the decrease in h_0. An observer forgetting this might mistakenly assume that these waves come from some instability in the shallow water region.

The "true" situation in a tokamak is complicated, with a turbulent spectrum coupled both nonlinearly and toroidally, propagating in an inhomogeneous medium. Here, we consider a simplified model of a slab plasma with a radial density gradient in a straight uniform magnetic field. The magnetic field is taken as unsheared, with the assumption that the localizing influence of magnetic shear is roughly offset by toroidal coupling. A drift wave of single poloidal mode number is launched in the high density "core," propagating radially outward. This simple model gives insight into the behavior of a drift wave approaching the low density "edge" region, including amplitude and wavelength variations, and whether the wave breaks or reflects.

A possible description of this mechanism is a wave kinetic equation, which can describe both linear propagation and nonlocal, nonlinear interaction effects. Such effects allow the wave excitation to spread, even in the presence of linear ion Landau damping. The formalism is easily extended to include effects of sheared flows, which can be generated naturally by propagating waves.

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Optimized Parallel Convolutions For Non-Linear Fluid Models Of Tokamak η_i Turbulence

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Non-linear computational fluid models of plasma turbulence based on spectral methods typically spend a large fraction of the total computing time evaluating convolutions. Usually these convolutions arise from an explicit or semi implicit treatment of the convective non-linearities in the problem. Often the principal convective velocity is perpendicular to magnetic field lines allowing a reduction of the convolution to two dimensions in an appropriate geometry, but beyond this, different models vary widely in the particulars of which mode amplitudes are selectively evolved to get the most efficient representation of the turbulence.

As the number of modes in the problem, N, increases, the amount of computation required for this part of the evolution algorithm then scales as N^2/timestep for a direct or analytic method and $N \ln N$/timestep for a pseudospectral method. The constants of proportionality depend on the particulars of mode selection and determine the size problem for which the methods will perform equally. For large enough N, the pseudospectral method performance is always superior, though some problems do not require correspondingly high resolution.

Further, the Courant condition for numerical stability requires that the timestep size must decrease proportionately as N increases, thus accentuating the need to have fast methods for larger N problems.

We have developed a package for the Cray system which performs these convolutions for a rather arbitrary mode selection scheme using either method. The package is highly optimized using a combination of macro and microtasking techniques, as well as vectorization and in some cases assembly coded routines. Parts of the package have also been developed and optimized for the CM200 and CM5 system.

Performance comparisons with respect to problem size, parallelization, selection schemes and architecture will be presented.

Three Dimensional Simulations of the Parallel Velocity Shear Instability

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We have performed fully nonlinear three-dimensional fluid simulations of the electrostatic parallel velocity shear instability as applied to a tokamak edge plasma. In the present study a source term in the parallel momentum equation drives the sheared parallel flow. Studied are the effects of magnetic shear on the turbulence of the mode and the associated fluctuation levels. The inclusion of the nonlinear polarization drift in the perpendicular dynamics is found to significantly affect the final nonlinear state. Dependence of the anomalous momentum transport on the magnetic shear and the gyroradius parameter, associated with the polarization drift, will be presented.

LBL-33630a

KINETIC TREATMENT OF MAGNETOSONIC WAVE REFLECTION BY MINORITY GYRORESONANT BALLISTIC WAVES IN TOKAMAK GEOMETRY*

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The analysis of the minority-ion gyroresonant heating process by a magnetosonic wave in a general magnetic field geometry with one ignorable spatial coordinate can be divided into several steps, each defined in terms of a precise mathematical problem to be solved. In this work, we focus our attention on the magnetosonic wave reflection problem in axisymmetric tokamak geometry; the conversion and absorption of the minority-ion gyroresonant ballistic waves are treated elsewhere.[1] In contrast to our previous work,[2] we employ a kinetic model based on the perturbation generating function[3] S for the gyroresonant minority-ions. The bulk plasma response is represented by the perturbation magnetic vector potential $\mathbf{A}$, corresponding to a shielded magnetosonic wave. The set of coupled equations for S and $\mathbf{A}$ can be derived from an action principle, which can also be used to derive explicit wave-action conservation laws in ray phase space. The reflection problem is solved in ray phase space by considering three separate steps. In the first step, the incident magnetosonic ray propagates towards the first linear mode conversion region, where action is transferred to the minority-ion gyroresonant ballistic waves. In the second step, the continuum of excited gyroresonant ballistic rays propagate towards the second linear mode conversion region. In the third step, the reflected magnetosonic wave field is excited by linear mode conversion from the minority gyroresonant ballistic rays.

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PROGRESS IN TRIANGULAR MAGNETOHYDRODYNAMICS*

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Many of the advances in our understanding of fusion plasmas over the past ten years has resulted from the application of techniques of large scale numerical simulation to three dimensional toroidal geometry. Since the dominant toroidal motions in a tokamak are generally long wavelength, finite Fourier series provides an efficient spatial representation for that coordinate. However, the next generation of numerical tokamak simulations will require that the poloidal cross section of actual experimental devices be more accurately represented. We address these difficulties by the application of an *unstructured adaptive mesh* to the representation of the poloidal plane, coupled with a finite Fourier representation of the toroidal coordinate. These meshes are not tied to a particular coordinate system, so that mesh points can be arbitrarily distributed to simulate the details of experimental apparatus. Since mesh points do not have a sequential orientation with their spatial neighbors, they can be easily added and deleted based on physical criteria. Evolving fine scale spatial structures are thus efficiently and accurately represented.

We have derived an algorithm for the solution of the resistive MHD equations on these meshes. This algorithm is based on the triangulation of arbitrarily distributed points in the plane; hence the term *triangular MHD*. The algorithm preserves the solenoidal properties of **B** and **J** identically, and is a generalization of staggered mesh techniques used in structured, rectangular grids. A new 3-D MHD code, TRIM, based on this algorithm has been developed. Preliminary results from TRIM will be presented.

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Numerical Simulation of Bootstrap Current*

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Abstract

The neoclassical theory of Bootstrap Current is confirmed by numerical simulation. The effects of ripple, loop voltage, magnetic and electrostatic perturbations on bootstrap current for the cases of zero and finite β are studied. The numerical results reasonably agree with the analytic estimation.

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Nonlinear Dynamics of the m=1 Instability and Fast Sawtooth Collapse in High-Temperature Plasmas

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An interesting, and as yet unresolved, issue of tokamak theory is the problem of *onset* of the sawtooth collapse (also known as the fast trigger problem). Though there are numerous models that can account for the typical timescale of a fast sawtooth crash, these models do not explain the mechanism by which a sudden and spontaneous transition occurs from the sawtooth ramp phase to the collapse phase.

In this paper, we propose an analytical model which provides a solution for the fast trigger problem. We investigate the nonlinear evolution of the m=1 instability governed by the generalized Ohm's law including the Hall term. Though the Hall term cannot break field-lines, it nevertheless has a profound influence on the dynamics of the instability because it introduces a new spatial scale of the order of the ion gyroradius ρ_i, which is the spatial scale of the parallel electric field $E_{||}$ near the singular layer. The spatial scale of the parallel current $J_{||}$ is narrower, and in a collisionless plasma, is of the order of the skin depth $\delta \equiv c/\omega_{pe}$.

We show that there are three distinct phases in the nonlinear dynamics of the m=1 instability : (1) a slow growth phase, (2) a near-explosive phase which accounts for the sudden onset of the sawtooth collapse, and (3) a rapid decay phase. In the slow growth phase, the m=1 island (of width w) exhibits Y-points, and a current sheet is formed at the separatrix near $r = r_s$. The dynamics is helicity-conserving (Waelbroeck, 1989), and the current sheet subtends an angle of $2\pi/3$ at the center of the plasma. In the near-explosive phase, the Y-points shrink dramatically. Assuming $w << r_s$, we show that the island width grows as $1/(t_c - t)$, where $t_c = 2r_s\Omega_i^{1/2} / (\omega_A^{3/2} w(0))$ and $\omega_A = (v_A/R)\, q' r_s$. (Here Ω_i is the ion Larmor frequency, v_A is the Alfven speed, q is the safety factor and R is the major radius.) The finite-time singularity predicted by the theory in the near-explosive phase is not realized in practice because the island grows to such a large size that the thin-island approximation $w << r_s$ breaks down. The inclusion of a correction term due to finite island-size $w \sim r_s$ then predicts rapid decay of the island as the reconnection process is completed. A master equation is derived for the nonlinear dynamics of the m=1 island, and describes all three phases.

The predictions of the analytical theory are in accord with the numerical simulations of Aydemir (1992) which provided the stimulus for this work, and experimental observations from JET (Wesson et al., 1991) and TFTR (McGuire et al.1990). In particular, measurements of the X-ray emissivity in JET of the plasma displacement ξ shows an average timescale $(d\ln\xi/dt)^{-1} \sim 25\ \mu s$ during the near-explosive phase; the prediction of our model for typical JET parameters is 15 µs. The model suggests that the observed timescales for the sawtooth crash can depend sensitively on the value of the magnetic shear at the q=1 surface. This may be one reason why current profiles in TFTR (or JET), which appear to be similar in their overall global features, exhibit sawtooth crashes that cover a fairly wide range in timescales.

NUMERICAL INVESTIGATION OF THE ION-TEMPERATURE-GRADIENT STABILITY OF DIII-D PLASMAS IN VARIOUS MODES OF ENERGY CONFINEMENT*

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A fast linearized gyrokinetic particle code (based on a δf algorithm) is used to investigate the stability of the ion-temperature-gradient (ITG) mode in DIII-D plasma discharges with different energy confinement modes: L-mode, H-mode, and VH-mode. The experimental density and temperature profiles for the ion and electron species as well as the numerically-calculated MHD equilibrium magnetic flux surface geometry are used as input data for the ITG-stability code. Our stability analysis is based on a simple physical model: only electrostatic fluctuations are considered, the perturbation fields are expressed in the ballooning-mode representation, the electrons are assumed to behave adiabatically, and the effects of impurity ions and energetic beam-ions are omitted. A complete treatment of circulating and trapped ion dynamics is, however, included for arbitrary mode frequencies compared with transit or bounce frequencies as well as arbitrary perpendicular wavelengths compared to the particle gyroradii and banana widths. Once a magnetic flux surface (labeled by the dimensionless variable ρ) and a toroidal mode number n are selected, a set of geometric functions (e.g., $k_\perp$, ω_{Di}, etc.) needed for solving the gyrokinetic equation is calculated from the equilibrium input data, and is transferred to the ITG-stability code. A growth-rate profile $\gamma(\rho; n)$ is generated by running the ITG-stability code for several different magnetic flux surfaces and fixed n. In the present work, we investigate the stability of (even-parity) ITG modes in the DIII-D plasma discharge No. 75121, at three times corresponding to the L-mode, H-mode and VH-mode energy confinement regime, respectively. A discussion of our numerical results will presented on the basis of relevant theoretical models.

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$m = 1$ Resistive Internal Reconnection in a Two Fluid Approximation

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The $m = 1$, $n = 1$ resistive reconnecting mode in a tokamak is investigated numerically in the two fluid approximation, using a version of the initial value code MH3DK[1]. The effect of introducing the Hall term $J \times B$ into the Ohm's law is discussed, first for the linear perturbation eigenmode and growth rate and then for the nonlinear evolution, in order to compare the effects to those involved in the crash phase of a sawtooth. Different plasma geometries are used to clarify different aspects of the process, in particular the two dimensional configuration with $m = 1$, $n = 1$ helical symmetry, corresponding to the usual analytical approximation, and also the full 3D toroidal geometry, where both include the effects of plasma compressibility. The effects of the diamagnetic frequencies $\omega_{*j} = (cT_j/B)(1/n)(dp_j/dr)$, $j = e, i$, and the corresponding rotation of the inner part of the plasma, which are introduced by the Hall term, are investigated. The role played by the Hall term relative to that of the electron pressure gradient in the Ohm's law is also considered. Linear perturbation results are compared with the theoretical results and the nonlinear evolution is discussed.

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Neutral gas transport modeling with DEGAS 2*

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We are currently re-writing the neutral gas transport code, DEGAS [1], with a view to making it both faster and easier to include new physics. We will present model calculations including ionization and charge exchange illustrating the way that reactions are included into DEGAS 2 and its operation on a distributed network of workstations.

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FASTWAC FOR FULL WAVE CURRENT DRIVE CALCULATIONS*

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FASTWAC is a full wave code designed for fast wave current drive calculations in tokamaks. The 3-D structure of fast wave electric and magnetic field components in a tokamak is calculated similar to the FASTWA code algorithm[1,2]. Numerical simulation of ohmic and bootstrap current is presented as well. The bootstrap current computed by using the Hirshman-Sigmar formulation[3,4]. RF driven current distribution is evaluated through the local power absorbed by electrons according to the Ehst-Karney expression[5] for the current drive efficiency incorporating trapped particle effect. Special attention is paid to correct calculation of the power absorbed by electrons through mechanisms of Landau damping, TTMP, and the cross-term effect. The current version of the FASTWAC code includes situations with the general ion cyclotron harmonic resonances located inside a plasma, and multiple plasma components and impurities with the different temperature and density profiles. Helicity and nonresonant RF driven currents[6] are discussed which stresses importance of the wave polarization factor for driving a current in a tokamak. Numerical examples for parameters of Phaedrus-T and TPX tokamaks are presented.

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Modelling of ultra high recycling divertors with the PLANET - TD code

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The handling of power carried by the charged particles into the scrape-off layer of a tokamak reactor remains a major obstacle for its continuous and reliable operation. Ways of reducing this power through radiation and charge-exchange have been studied using the PLANET-TD code which employs 2-D fluid models for both the plasma and neutral gas transport. Divertor plasma temperatures as low as 1eV have been achieved resulting in an ionization-free region together with an ionization front detached from the material walls. This feature is essential for the charge-exchange energy transport schemes. A number of solutions with large radiative, hydrogen and impurity, energy dissipation have been found. The usefulness of these regimes in tokamak reactors is discussed.

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FAST WAVE FLOW DRIVE IN A TWO-ION-COMPONENT PLASMA

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Shear flow drive utilizing externally injected RF waves has been proposed sometime ago[1] as means of active control of tokamak confinement. Such scheme of flow drive has the desirable features that the location, the width, and the strength of the shear layer are externally controllable. Here we investigate the scenario of flow drive using FAST WAVES. The flow drive using high frequency fast wave is advantageous over the low frequency shear Alfven waves in two respects: (1) the fast wave can easily propagate into the core of a plasma, and suppress core fluctuations by driving a shear flow there; (2) the Reynolds stress and the $\vec{J} \times \vec{B}$ force, which are responsible for the flow drive, do not tend to cancel each other. In particular, we show that the Reynolds Stress is the dominant force for flow drive. Using the hot plasma kinetic theory, we have calculated the profiles of the mean flow, namely the magnitude and the width of the shear flow, and the RF power absorbed. Also, the power threshold for suppression of turbulence, thereby improving tokamak confinement, is given.

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Resonant Interaction of Alphas with TAE-Modes

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Toroidal Alfven Eigenmodes induced by energetic ions has received great attention in the fusion research community for the past few years. In this work, the resonant behaviors of alpha particles interacting with TAE-modes are studied using the Hamiltonian guiding center code (ORBIT). In addition, the resonant surfaces in the constants of motion phase space (E, μ, P_φ) are calculated numerically using the same equilibrium as used in ORBIT code and the resonant condition $\omega = N < \omega_\varphi > -M < \omega_\theta >$. Here the angle bracket denotes the bounce average. The resonance condition obtained from both approaches agree perfectly. It is found that there is strong bounced resonance from deeply trapped particles even when the toroidal number $N = 1$. Conversely, when $N > 1$, toroidal precession resonance becomes more and more important.

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Instability near the Minority Ion Cyclotron Resonance

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In warm plasmas containing an energetic minority ion species, such as the earth's magnetosphere and an rf-heated fusion plasma, the fast magnetosonic wave and the ion acoustic wave have a resonance ($k \to \infty$) near the minority ion cyclotron frequency and its harmonics. Near these resonances strong absorption of the wave takes place, resulting in ion cyclotron heating and an anisotropic distribution of ion velocities. This velocity space anisotropy may in turn give rise to instability. Here we study, analytically and numerically, instability near the fast-wave minority ion cyclotron resonance and its second harmonic according to linear Vlasov-Maxwell theory. In the context of a fusion reactor, we assume a minority ^{3}He population modeled by an anisotropic (bi-Maxwellian) velocity distribution function with $T_\perp > T_{//}$ in a background plasma of isothermal deuterium and electrons. All species are uniformly magnetized. Thresholds for the instability are indicated in terms of the temperature ratio $T_\perp / T_{//}$ and minority ^{3}He concentration for various angles of fast-wave propagation to the background magnetic field. Parameters are typical of the JET reactor.

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MHD Simulation on an Unstructured Mesh

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Two dimensional time dependent RMHD equations are solved numerically on an unstructured mesh of triangular elements. An unstructured mesh is useful for simulations of divertor tokamaks containing a magnetic separatrix. A finite element discretization is used. The resulting sparse matrices are solved by the Incomplete Cholesky Conjugate Gradient algorithm. The matrix equations are time advanced by implicit, semi implicit, and explicit methods. Thermal diffusion along the magnetic field handled implicitly. A semi implicit option for the momentum equation allows time steps considerably larger than the shear Alfvén transit time. Methods for adaptive regridding are being developed.

Some applications, which will be presented, include the nonlinear m=1 tearing mode, the two dimensional tilt instability, rotating MHD equilibria, and equilibria in divertor tokamaks.

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AN ANALYTICAL MODEL OF COUPLED FLUCTUATION AND FLOW DYNAMICS IN SELF-REGULATING TURBULENCE

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It is now well established that fluctuations and sheared flows are strongly coupled at the plasma edge. Fluctuations are regulated by flow profile, especially curvature, while flows are driven by fluctuation Reynolds stresses. The coupled system defines a dynamically self-regulated shear flow turbulence.

Here, we analytically investigate a simple drift wave model of shear flow turbulence. Analytical evolution equations for flow curvature and mean square fluctuation level are derived. Two equilibria, one corresponding to no flow (L-mode) and one to finite flow (H-mode) are found. In the finite flow equilibrium, fluctuation levels are determined primarily by flow dissipation, rather than by linear instability parameters. The stability conditions for each equilibria and the eigen-frequencies for modulational oscillations about each equilibrium are calculated. The 'basin of attraction' for the "H-mode" equilibrium is determined. The bifurcation criterion is that $\tilde{n}/n$ exceed the critical level for flow curvature growth.

In addition to its obvious relevance to L$\rightarrow$H transition physics, this work has the broader implications that:

a.) an actual edge plasma may often be in a state of dynamical non-equilibrium

b.) fluctuation stability calculations must address flow modulations and evolution.

Dynamo and Diffusion Processes in a Reversed Field Pinch

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The dynamo strucure in the reversed field pinch (RFP) is studied through the nonlinear dynamics of single-helicity and multi-helicity resistive modes. Simulation is concentrated upon the physical structure of nonlinear interactions of the plasma flow and magnetic fluctuation [1]. The result indicates that when the initial equilibrium profile is deformed by resistive diffusion, the radial flow is driven near the core of the plasma. As this flow forms a vortex structure and magnetic fluctuation grows radially, the dynamo electric field is helically induced just inside the reversal surface and then the toroidal flux is increased. This dynamo electric field correlates to nonlinear evolution of the kinetic energy of m=1 mode, and the increase of the toroidal flux is originated from the growth process of the magnetic energy of this mode. Consequently, the RFP configuration can be sustained by the single-helicity evolution of m=1 mode alone, and the electric field induced by the interactions of the toroidal velocity and the radial magnetic field is the most dominant source on the dynamo action. By mode coupling processes, the single helicity state eventually evolves to the multii-helicity turbulent state in which the reversed field configuration is maintained.

Transport in a realistic reversed field pinch (RFP) configuration is studied numerically for neoclassical and MHD fluctuation transport mechanisms, by Monte Carlo simulation [2]. The results indicate that neoclassical transport due to guiding center drift is one or two orders lower than classical transport due to finite gyro-motion and thus, is not important for RFP plasmas. However, the electron diffusion coefficient corresponding to a typical MHD fluctuation configuration of the magnetic Reynolds number $S=10^4$, is about 10^6 cm^2/sec which is two orders higher than the classical transport, and is an important transport loss mechanism for RFP plasma confinement.

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Effective Resistivity and Heat Conduction in a Stochastic Magnetic Field

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Transport in a stochastic magnetic layer is an important issue in tokamak physics which finds a stimulating counterpart in experiments where the stochasticity is controlled by a set of specific coils, as in Tore Supra (Ergodic Divertor) or on TEXT (Ergodic Magnetic Limiter). In this paper we first recall the results obtained for particle transport. Using the same method of functional extremum calculation we investigate the regime of weak stochasticity due to the finite connection length to the wall L_{wall}. In this case one has $L_{\text{wall}} \lesssim L_{\text{K}}$ where L_{K} is the Kolmogorov scale of the stochastic magnetic field. This regime is readily expected in the experiments and governs the heat deposition through the so-called laminar domain [1]. In the ergodic domain we use again this method to calculate the effective resistivity along the toroidal direction. We find that in all cases there is a strong increase of this resistivity which will account for the narrowing of the current channel and eventually for the stabilization of the MHD (2.1) mode.

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Wave Kinetic Description of Lower-Hybrid Absorption in Tokamaks

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The wave kinetic equation (WKE) describes the propagation and absorption of short wavelength modes and can be an effective method to treat multi-pass absorption and wave chaos, which is important in lower-hybrid current drive [1]. In the WKE, action density (or energy density in a stationary medium) is convected along ray-trajectories in the $(\boldsymbol{k},\boldsymbol{x})$ phase space, where $\boldsymbol{k}$ is the wave vector and $\boldsymbol{x}$ is the position vector [2]. We first consider the cylindrical tokamak model, for which the exact wave equation is separable. For a mode launched at the plasma edge (with given poloidal and toroidal mode numbers), solutions of the WKE give the radial profile of the energy density and absorbed power. We find these to be in good agreement with numerical solutions obtained from a full wave code [3]. This is true for either single pass, or multi-pass absorption, including the case of cold plasma mode conversion. In toroidal geometry, the poloidal number is not conserved and stochastic layers develop in ray phase space. For a thick stochastic layer, one may appropriately average over the poloidal angle and radial coordinate (in ray phase space) to obtain a one-dimensional diffusion equation, with damping and sources, for the wave energy density as a function of poloidal number. The damping term in this equation depends on the fast electron distribution function, which has an implicit (quasilinear) dependence on the wave parallel electric field energy. Steady-state solutions of this coupled nonlinear system are obtained numerically for various current drive scenarios. The results show that there is a strong quasilinear flattening of the electron distribution throughout the resonant region (including the spectral gap), except in a narrow boundary layer at low phase velocity. One interesting consequence of this is that the power absorption profiles are essentially independent of both the total injected power and the wave stochastic diffusion coefficient.

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Model for ICRF Fast Wave Current Drive in Self-Consistent MHD Equilibria*

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Recently, a model for fast wave current drive in the ion cyclotron radio frequency (ICRF) range was incorporated[1] into the current drive and MHD equilibrium code ACCOME. The ACCOME model[2] combines a free boundary solution of the Grad Shafranov equation with the calculation of driven currents due to neutral beam injection, lower hybrid (LH) waves, bootstrap effects, and ICRF fast waves. The equilibrium and current drive packages iterate between each other to obtain an MHD equilibrium which is consistent with the profiles of driven current density.

The ICRF current drive package combines a toroidal full-wave code (FISIC)[3] with a parameterization of the current drive efficiency[4] obtained from an adjoint solution of the Fokker Planck equation. The electron absorption calculation in the full-wave code properly accounts for the combined effects of electron Landau damping (ELD) and transit time magnetic pumping (TTMP), assuming a Maxwellian (or bi-Maxwellian) electron distribution function.[5] Furthermore, the current drive efficiency includes the effects of particle trapping, momentum conserving corrections to the background Fokker Planck collision operator, and toroidally induced variations in the parallel wavenumbers of the injected ICRF waves.

This model has been used to carry out detailed studies of advanced physics scenarios in the proposed Tokamak Physics Experiment (TPX). Results will be shown for example, which demonstrate the possibility of achieving stable equilibria at high beta and high bootstrap current fraction in TPX. Model results will also be shown for the proposed ITER device.

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Parallel Computation and the Basis System*

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A software package has been written that can facilitate efforts to develop powerful, flexible, and easy-to-use programs that can run in single-processor, massively parallel, and distributed computing environments. Particular attention has been given to the difficulties posed by a program consisting of many science packages that represent subsystems of a complicated, coupled system. Methods have been found to maintain independence of the packages by hiding data structures without increasing the communication costs in a parallel computing environment. Concepts developed in this work are demonstrated by a prototype program that uses library routines from two existing software systems, Basis and Parallel Virtual Machine (PVM). Most of the details of these libraries have been encapsulated in routines and macros that could be rewritten for alternative libraries that possess certain minimum capabilities. The prototype software uses a flexible master-and-slaves paradigm for parallel computation and supports domain decomposition with message passing for partitioning work among slaves. Facilities are provided for accessing variables that are distributed among the memories of slaves assigned to subdomains. Combinations of computational resources that can be utilized include a network of workstations (not necessarily of the same architecture) and a single workstation (master) controlling one or more supercomputers (slaves). The computational resources can be allocated among science packages in many different ways allowing either concurrent or sequential execution of the packages.

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Microinstability Studies of Advanced Tokamak Configurations*

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Advanced tokamak configurations attempt to make use of both cross-sectional shaping and profile control to enhance the stability properties of the plasma. A comprehensive kinetic toroidal eigenvalue calculation[1] which implements the ballooning formalism is employed to investigate this for high-n instabilities such as the toroidal drift mode destabilized by the combined effects of ion temperature gradients and trapped particles. One configuration which has recently had very interesting experimental results is the very-low-aspect-ratio START tokamak[2]. For aspect ratios less than about two, the linear instability calculations show a strong stabilizing trend for this device which has a D-shaped cross section. The same calculations for circular and "comet"-shaped[3] cross sections show similar trends. Another cross-sectional shape which has been considered is the "bean"-shape, which is indented on the small-major-radius side. Again, the instability calculation shows increasing stabilization with increasing indentation for generic bean-shaped cases. Another approach being pursued in advanced tokamak configurations is profile control for the current and/or pressure. In particular, it may be possible to produce regions of reversed shear ($dq/dr < 0$), as has been observed in the JET tokamak in PeP mode discharges. The effects of this reversed shear are being investigated with the same instability calculation.

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A New Interpretation of the Ballooning Mode Representation Formalism*

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Using a new eikonal form of the eigenmode and a new coordinate system similar as the *twisted eddy coordinate*[1] we provide a different point of view of the ballooning mode representation formalism. In our model, the ballooning mode equation appears as a partial differential equation along the characteristic line and the familiar Bloch shift parameter θ_0 represents the label of the characteristic lines. The eigenvalues appears to be periodic in term of θ_0 and from this periodicity we can obtain easily the eigenfunction which is periodic in the real θ space. Taking the inverse coordinate transform to the real space, the eigenfunction now takes the form of the ballooning mode representation. In terms of this new point of view of the ballooning mode representation formalism, various related issues such as the determination of the envelop profile, the inclusion of the equilibrium shear flow effect[2], and the relation with the 3D nonlinear ballooning mode representation[3] will be discussed.

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MHD Properties of Advanced Plasma Configurations†

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The ability to control the current profile in a tokamak by using non-ohmic current drive opens up the possibility of new modes of operation with enhanced stability properties and/or with most of the current being produced by the bootstrap effect. We have carried out intensive theoretical studies of the stability properties of such plasmas, of the physics parameters needed to optimize them, and of the scaling relations which allow us to prototype certain advanced tokamak reactor features in smaller experiments such as PBX-M. We have found some operational modes with very peaked pressure profiles that are stable to all modes with values of $\beta_N{}^* > 6.3$ and $q_* = 2.3$. Other modes of operation can be optimized to align the bootstrap current to within 5% of the plasma current, with values of $\beta_N = 5.36$ at $q_* = 5$. Methods for increasing the parameters even further using negative edge currents are discussed, as is the requirement for needing extreme accuracy and convergence studies when using the PEST code in these advanced regimes.

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Neoclassical MHD Modified Eigenmode Equations For Internal Kink Modes In Tokamak Plasmas*

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Both anomalous loss of energetic particles[1] and sawtooth oscillations in tokamak plasmas are thought to be related to the evolution of $m = 1$ internal kink modes. Research work in this area seems to become increasingly active as intensive fusion reactions come close to realization in some large tokamak devices. So far resistivity and Larmor radius effects have been discussed in the transition layer of internal kink modes[2], but effects related to long mean free path (neoclassical MHD effects) mostly remain to be studied. In this work, starting from a set of simplified neoclassical MHD equations[3,4], we derive eigenmode equations for internal kink modes in the transition layrer near the $q = 1$ surface by using the ballooning mode representation and a multiple length scale approximation. For comparing the results with the usually assumed MHD or resistive MHD eigenmode equations, the equations are transformed from the ballooning mode representation to ordinary space after averaging over a magnetic surface. The neoclassical MHD effects substantially modify the usually assumed MHD or resistive MHD eigenmode equations for internal kink modes, and reduce the growth rate of these modes — because of the enhanced neoclassical inertia for these slowly growing modes.

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The Importance of Three-Dimensional Effects for Antenna Modeling*

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Electromagnetic field calculations for radio frequency (RF) antennas in two-dimensions (2-D) neglect finite antenna length effects as well as the feeders leading to the main current strap. Comparisons with experiment indicate that these 2-D calculations give reasonable estimates for the overall loading of the antenna, but fail to give the correct circulating power. The 2-D calculations also predict that the return currents in the side walls of the antenna structure depend strongly on the plasma parameters, but this prediction is also suspect because of experimental evidence and three-dimensional (3-D) modeling results. To study the validity of the 2-D approximation, the MAntIS (Multiple Antenna Implementation System) code has been used to perform 3-D modeling of the power spectrum, plasma loading, and circulating power for loop antenna designs. The plasma impedance matrix for the calculation is generated using the ORION-1D code. Contributions to the circulating power from the feeders cause the 3-D results to be in much more reasonable agreement with experiment than the 2-D predictions. The modeling shows that the feeders also affect the launched power spectrum in an indirect way by strongly influencing the location and magnitude of return currents in the side walls of the antenna structure. In the 3-D model all of the driven RF current is forced to return in the antenna structure whereas the 2-D model allows the driven RF current to return in the plasma. The 3-D modeling shows that the feeders have much more influence than the plasma on the currents that return in the side wall. The super-position approximation has also been explored in 3-D for antennas that are side by side with different RF phasing. Preliminary results indicate that super-position is a reasonable approximation when phased current straps are separated by a conducting septum, thereby permitting rapid approximations to the launched power spectrum for some current drive antenna arrays.

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Plasma Energy for Electromagnetic Perturbations*

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Following previous work[1], the exact plasma free energy expression, $\delta^2 F$, for electromagnetic perturbations about a homogeneous equilibrium is obtained and compared to the dielectric energy, $\mathcal{E}_{\mathcal{D}}$. The Vlasov–Maxwell system is linearized about a homogeneous equilibrium. A closed set of moment equations for the perturbed distribution function is then obtained. These equations are solved for an arbitrary initial perturbation using Van Kampen modes[2]. The free energy, expressed in terms of the moments of the perturbed distribution function, is then evaluated using this solution. The resulting energy expression breaks naturally into longitudinal and transverse contributions.

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Alfvén-wave Current Drive and Magnetic Field Stochasticity

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Propagating Alfvén waves can generate parallel current through an alpha effect. In resistive MHD however, the dynamo field is proportional to resistivity and as such cannot drive significant currents for realistic parameters. In the search for an enhancement of this effect we investigate the role of magnetic field stochasticity. We show that the presence of a stochastic magnetic field, either spontaneously generated by instabilities or induced externally, can enhance the alpha effect of the wave. This enhancement is caused by an increased wave dissipation due to both current diffusion and filamentation. For the range of parameters of current drive experiments at Phaedrus-T tokamak, a moderate field stochasticity leads to significant modifications in the loop voltage.

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Two-Dimensional Eigenmode Analysis of Long-Wavelength Microinstabilities in Rotating Axisymmetric Plasmas*

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We present a two-dimensional study of sheared flow effects on the kinetic trapped-ion and toroidal ion temperature gradient instabilities. The governing electrostatic gyrokinetic equation for rotating axisymmetric plasmas with Mach numbers of order unity is formulated. In the long-wavelength limit, $(k_r \rho_{bi} < 1)$, this equation is solved utilizing an improved version[1] of the toroidal finite element code[2]. Earlier local studies[3] found that sheared toroidal flows will have a destabilizing effect on the trapped ion instability in both collisional and collisionless regimes. This effect is mainly due to the fact that the fraction of trapped particles is increased through electrostatic trapping. The ions are pushed outward due to centrifugal force and an electrostatic potential is set up by the electrons to achieve quasineutrality. The poloidal dependence of this potential in turn increases the number of trapped particles. In this work we present results of the two-dimensional eigenmode analysis and discuss the implications of sheared toroidal flows on long-wavelength drift-type micro-instabilities in tokamaks.

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