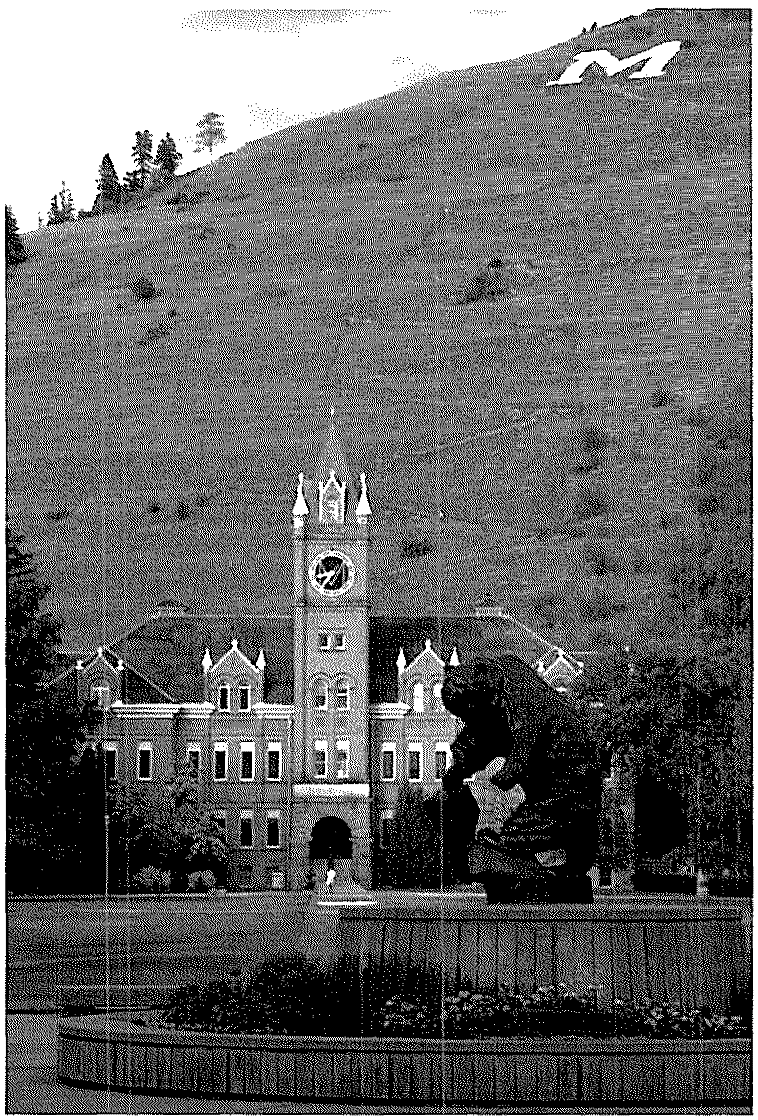
2004 International Sherwood Fusion Theory Conference April 26-28, 2004 Missoula, Montana

2004 International Sherwood Fusion Theory Conference

April 26-28
Missoula, Montana



Hosted by Members of the
Department of Physics and Astronomy
The University of Montana

Saralyn Stewart

International Sherwood Fusion Theory Conference

April 26-28, 2004
Doubletree Hotel Missoula
Missoula, Montana

Hosted by Members of the
Department of Physics and Astronomy
The University of Montana

Executive Committee
Tom Rognlien (*Chair*), LLNL
Philip Snyder (*Vice-Chair*), General Atomics
Greg Hammett (*Secretary/Treasurer*), PPPL
Curt Bolton, U.S. Department of Energy
Paul Bonoli, MIT
John Cary. University of Colorado
Diego del-Castillo Negrete, ORNL
Daniel D'Ippolito, Lodestar Research Corp
Richard Fitzpatrick, University of Texas
Alan Glasser, LANL
Parvez Guzdar, University of Maryland
Paul Terry, University of Wisconsin
Linda Vahala, Old Dominion University

Local Organizing Committee
Andrew Ware (*Chair*), University of Montana
Daniel D'Ippolito, Lodestar Research Corp
Jeremy Sauer, University of Montana
Paul Terry, University of Wisconsin
Eijiro Uchimoto, University of Montana
David Westerly, University of Montana

Program Committee
Chris Hegna (*Chair*), University of Wisconsin
Glenn Bateman, Lehigh University
Alan Glasser, LANL
Lynda Lodestro, LLNL
Scott Parker, University of Colorado
Andrew Ware, University of Montana

Administrative Staff
Saralyn Stewart, University of Texas
Michele Kratz, University of Montana
Cindy Henderson, LLNL

Cover photo: University Hall of the University of Montana (built in 1898). In the foreground is the Grizzly Statue and in the background is Mount Sentinel and the M trail, a popular hike from campus.

Registration Schedule

Sunday, April 25	18:00 to 21:00
Monday, April 26	7:30 to 11:30 and 13:00 to 17:00
Tuesday, April 27	7:30 to 11:30
Wednesday, April 28	7:30 to 10:00

Social Schedule

Sunday, April 25	19:00 to 21:00	*Welcome Reception*
Monday, April 26	8:30 to 10:00	*Companions Breakfast*
Monday, April 26	15:00 to 17:00	*Stellar Navigation of Lewis & Clark*
Tuesday, April 27	12:00 to 17:30	*Free Afternoon*
Tuesday, April 27	12:30 to 17:00	*Excursion: Rafting the Clark Fork*
Tuesday, April 27	18:00 to 19:30	*Conference Banquet*

Program Organization

The program consists of 3 invited review papers, 14 oral contributed papers selected out of 34 oral submissions, and poster presentations. The total number of presentations is 176. Satellite meetings are also scheduled during the conference.

Meeting Program

All technical sessions will be held in the Doubletree Hotel Missoula, Main Ballroom.

- The **review talks** will be held at 8:30 Monday through Wednesday (1A, 2A, 3A)
- The **oral sessions** will be held:
  - 1B at 9:30 Monday morning
  - 1D at 13:30 Monday afternoon
  - 2B at 9:30 Tuesday morning
  - 2D at 7:30 Tuesday evening
  - 3B at 10:00 Wednesday morning
- The **poster sessions** will be held:
  - 1C at 10:00 Monday morning
  - 1E at 15:30 Monday afternoon
  - 2C at 10:00 Tuesday morning

Satellite Meetings

NIMROD Meetings

Saturday, April 24, 8:30 to 18:00 and Sunday, April 25, 8:30 to 12:00
University Room, Doubletree Hotel Missoula, 2nd level

Edge Working Group

Sunday, April 25, 15:00 to 18:00
Canyon Room, Doubletree Hotel Missoula, Lobby level

Theory Coordinating Committee Meeting

Monday, April 26. 20:00 to 22:00
Canyon Room, Doubletree Hotel Missoula, Lobby level

Sherwood Executive Committee Meeting

Tuesday, April 27, 12:30 to 15:30
University of Montana Room, Doubletree Hotel Missoula, 2nd level

Poster Sessions

Poster Session 1C
Monday, April 26, 10:00 to 12:00, Lewis & Clark Ballrooms

1C01 J. Manickam, R, Jayakumar, and M. Okabayashi
"Simulation of MSE signals, as a diagnostic tool for MHD instabilities"

1C02 C. McDevitt and P. H. Diamond
"Dynamic Sub-Grid Scale Modeling of Tearing Mode Interaction with Turbulence"

1C03 L. E. Zakharov, S. N. Gerasimov, and G. V. Pereverzev
"Equilibrium reconstruction and tokamak simulations with ESC-ASTRA"

1C04 P. W. Terry, R. Gatto, and D. A. Baver
"A comprehensive look at saturation dynamics of trapped electron mode turbulence"

1C05 K. J. Comer, J. D. Callen, C. C. Hegna, A. D. Turnbull, S. C. Cowley
"Predicting Ideal MHD Stability From Perturbed Equilibria: Successful Wall Perturbations and Limitations from Compressional Alfven Energy"

1C06 P. S. Coppi and B. Coppi
"Physics of Plasma Accretion Disks"

1C07 E. Hameiri
"The Complete Set of Casimir Constants of the Motion in Magneto-Hydrodynamics"

1C08 E. A. Keyes and B. Coppi
"Axisymmetric Modes in Thin Accretion Disks: Limits on Beta"

1C09 A. Y. Aydemir and J. J. Ramos
"Reconnection studies using a collisionless fluid closure model"

1C10 V. A. Izzo, T. R. Jarboe, and P. E. Sieck
"Spheromak Formation by Steady Inductive Helicity Injection in 3D MHD Simulations"

1C11 A. N. Simakov, A. H. Glasser, V. S. Lukin, and X. Z. Tang
"Application of the Spectral Element Code (SEL) to Edge Plasma Modeling"

1C12 V. A. Svidzinski and S. C. Prager
"Effects of particles with large gyroradii on magnetohydrodynamic stability"

1C13 J. D. Callen
"Paleoclassical Electron Heat Transport In Toroidal Plasmas"

1C14 Z. Wang and X. Z. Tang
"Chandrasekhar equilibria of compact toroids with Alfvénic flows"

Poster Sessions

1C15 W. W. Lee, S. Ethier, W. X. Wang, and Z. Lin
"Alfven Waves in Gyrokinetic Plasmas and Transport Time Scale Simulations"

1C16 F. W. Perkins
"On the Electric Pedestal"

1C17 K. Molvig, Y. Xiao, D. R. Ernst, and K. Hallatschek
"Enhanced Neoclassical Polarization, Zonal Flow Suppresion and Elevated Turbulence in Tokamaks"

1C18 G. Lapenta, J. U. Brackbill, W. Daughton, and P. Ricci
"3D Reconnection: onset and topology"

1C19 J. W. James and E. D. Held
"Electron Heat Confinement in Reversed Field Pinches"

1C20 R. Torasso and E. Hameiri
"Stability Study of the Hall-MHD Model"

1C21 K. C. Shaing
"Symmetry Breaking Induced Plasma Viscosity and Resistive Wall Mode"

1C22 S. J.Allfrey and S.Brunner
"Generalised evolving background f0 for plasma delta-f Particle-in-cell simulations"

1C23 V. Roytershteyn and B. Coppi
"Transport of Thermal Energy and its Relation to the Spontaneous Rotation Phenomenon"

1C24 W. Wan, Y. Chen, and S. E. Parker
"delta-f Simulation of collisionless and semi-collisional Tearing Modes"

1C25 R. B. White and D. A. Gates
"Transport and bootstrap current in a small aspect ratio torus"

1C26 Ö. D. Gürcan and P. H. Diamond
"Radial spreading of electron temperature gradient driven turbulence"

1C27 A. Dieter and R. D. Hazeltine
"Fluid description of ion dynamics in a toroidally confined plasma"

1C28 Y. Chen and S. E. Parker
"Effects of Flux Surface Shape on Turbulent Transport and a Modification of the Split-weight Scheme"

1C29 C. Jones, J. M. Finn, and L. Chacon
"Control of resistive wall modes – comparison of normal and tangential B sensing"

Poster Sessions

1C30 Y. Li and Z. Lin
"Electron Thermal Transport in Tokamak: ETG or TEM Turbulences?"

1C31 X.Liu and C.C.Hegna
"The Effects of Energetic Ions on Magnetic Islands in Toroidal Plasmas"

1C32 Y. Nishimura, Z. Lin, L. Chen, J. Lewandowski, S. Ethier, and W. Wang
"Electromagnetic gyro-kinetic simulation with a fluid-kinetic hybrid electron model"

1C33 R. Samtaney and S. Jardin
"Simulation of Pellet Injection in Tokamaks using 3D Adaptive Mesh Refinement"

1C34 A. H. Boozer
"Stability of pure electron plasmas on magnetic surfaces"

1C35 N. N. Gorelenkov, H. L. Berk, and R. V. Budny
"Alfven Eigenmode stability with beams in ITER-like plasma"

1C36 E. A. Belli, G. W. Hammett, W. Dorland, and R. V. Budny
"Studies of plasma shaping effects on ITG/TEM turbulence with the GS2 gyrokinetic code and a local linear gyrokinetic code"

1C37 G. Y. Fu and H. L. Berk
"Kinetic Damping of Toroidal Alfven Eigenmode Revisited"

1C38 B.A. Carreras, D. del-Castillo-Negrete, and V.E. Lynch
"High confinement modes with radial structure"

1C39 E. G. Evstatiev, W. Horton, and P. J. Morrison
"Hybrid multi-wave model for relativistic wave-plasma interaction"

1C40 R. Woodard, D. Newman, R. Sanchez, and B. A. Carreras
"Distinguishing Characteristics of SOC-like Systems"

1C41 M. V. Umansky, R. H. Bulmer, D. N. Hill, L. LoDestro, H. McLean, W. M. Nevins, D. D. Ryutov, and S. Woodruf
"Modeling of magnetic perturbations and energy confinement in SSPX spheromak"

1C42 R. A. Kolesnikov and J. A. Krommes
"Bifurcation analysis of the Dimits shift: Conceptual issues and resolutions"

1C43 D. A. D'Ippolito, J. R. Myra, and D. A. Russell
"Theory of Rapid Transport by 3D Blobs"

Poster Sessions

1C44 J. R. Myra, D. A. D'Ippolito, and D. A. Russell
"Convective transport in the scrape-off-layer by non-thermalized spinning blobs"

1C45 D. A. Russell, D. A. D'Ippolito, J. R. Myra, W. M. Nevins, and X. Q. Xu
"On the Structure of Blobs in Turbulent BOUT Simulations"

1C46 D. Gates and R. White
"Transport and bootstrap current in a small aspect ratio torus"

1C47 H. R. Strauss, W. Park, S. Jardin, J. Breslau, A. Pletzer, L. Sugiyama, and R. Paccagnella
"Nonlinear Resistive Wall Simulations"

1C48 F. L. Hinton, R. E. Waltz, and J. Candy
"Electromagnetic Turbulence Modification of Neoclassical Transport"

1C49 H. Qu, L. Chen, and Z. Lin
"Gyrokinetic Theory of Mirror Instability"

1C50 D. D. Schnack, D. C. Barnes, C. R. Sovinec, and the NIMROD Team
"Extended Fluid Models and Their Implications for Simulation Algorithms"

1C51 Y. Xiao and K. Molvig
"Broken Symmetry in Neoclassical Transport Theory"

1C52 W. M. Nevins, B. I. Cohen, A. Dimits, and D. Shumaker
"Statistical Analysis of ITG Turbulence"

1C53 C. S. Chang, S. Ku, and H. Weitzner
"Monte Carlo Guiding-Center Simulation of Neoclassical Edge Pedestal Formation and Study of Pedestal Scaling Law"

1C54 A. G. Tarditi
"Fluid Simulation of Plasma Flow in a Magnetic Nozzle"

Poster Sessions

Poster Session 1E
Monday, April 26, 15:30 to 17:30, Lewis & Clark Ballrooms

1E01 G. J. Marklin
"Taylor States in the HIT-SI Experiment"

1E02 V. V.Mirnov, C. C.Hegna, and S. C. Prager
"Effect of plasma relaxation and dynamo on mean current and electric field in the reversed field pinches"

1E03 L.-J. Zheng, M. Kotschenreuther, M. S. Chu, M. Chance, and A. Turnbull
"Stability of resistive wall modes with liquid metal blankets"

1E04 G. N. Throumoulopoulos and H. Tasso
"Hall-MHD axisymmetric equilibria with flow"

1E05 T. D. Rognlien, M. V. Umansky, X. Q. Xu, R. H. Cohen, W. M. Nevins, and D. D. Ryutov
"Characteristics of tokamak edge-plasma turbulence from 3D simulations"

1E06 N. Daniels, A. S. Ware, D. E. Newman, and C. Hidalgo
"Density Threshold for Edge Poloidal Flow Generation in a Transport Model"

1E07 J. D. Hanson, S. P. Hirshman, S. F. Knowlton, L. Lao, and E. A. Lazarus
"Equilibrium Reconstruction in Stellarators: V3FIT"

1E08 C. C. Kim, C. R. Sovinec, S. E. Parker, and the NIMROD Team
"Hybrid Kinetic-MHD Simulations in General Geometry"

1E09 J. B. Aydemir and A. Y. Aydemir
"Equilibrium and stability of rotating plasmas in a mirror geometry"

1E10 S. C. Jardin
"Extended MHD calculations with high order-of-continuity finite elements"

1E11 A. I. Smolyakov, S. I. Krasheninnikov, G. Q. Yu, and P. H. Diamond
"Large Scale Convective Structures and Instabilities in Edge Plasmas"

1E12 V. Tangri, R. Singh, and P. Kaw
"Electromagnetic Electron Temperature Gradient Modes in a Tokamak"

1E13 A. Cardinali and F. Zonca
"Analytical and numerical study of the lower-hybrid-relevant wave equation in a toroidal plasma"

1E14 P. G. Watson and F. Porcelli
"Exact steady-state reconnection solutions in weakly collisional plasmas"

Poster Sessions

1E15 J. L. V. Lewandowski, Y. Nishimura, W.W. Lee, Z. Lin, and S. Ethier
"Global Gyrokinetic Particle-in-cell Simulations with Trapped Electrons "

1E16 S. C. Prager, V. A. Svidzinski, and V.V.Mirnov
"Ion heating by collisional damping of tearing modes"

1E17 P. J. Morrison and G. R. Flierl
"Water Bags and Contour Dynamics"

1E18 J.-N. Leboeuf, V. Decyk, A. Dimits, and D. Shumaker
"Summit Framework: Gyrokinetic calculations of ITG turbulence in general toroidal geometry"

1E19 G. Bateman, A.H. Kritz, T. Onjun, A. Pankin, I. Voitsekhovitch, and S. Snyder
"Unresolved Issues in the Simulation of H-mode Pedestal and ELMs in Tokamaks"

1E20 E. Uchimoto, J. A. Goetz, R. O'Connell, S. C. Prager, and M. A. Thomas
"Improved Numerical Modeling of Lower Hybrid Experiments in the MST Reversed Field Pinch"

1E21 S. E. Sharapov
"1D Model for Alfvén Cyclotron Instabilities in the Spherical Tokamak Fusion Power Plant"

1E22 A. Apte, A. Wurm, and P. J. Morrison
"Separatrix Reconnection and Meanders in the Standard Nontwist Map"

1E23 D. D. Ryutov and R. H. Cohen
"Enhancement of the divertor-leg instability by tilting of the divertor plate"

1E24 S. Wang, A. S. Ware, S. P. Hirshman, and D. A. Spong
"A Breeder Algorithm for Stellarator Optimization"

1E25 J. C. Wiley, M. Kotschenreuther, and P. Valanju
"The discontinuous Galerkin method applied to SOL transport"

1E26 P. N. Guzdar, S. M. Mahajan, and Z. Yoshida
"Equilibrium theory of the pressure pedestal in High (H) mode tokamak plasmas"

1E27 A. M. Dimits, W. M. Nevins, and D. E. Shumaker
"Sources and Sinks in the Zonal Flow Energy Balance in Tokamak Microturbulence"

1E28 C. Z. Cheng and N. N. Gorelenkov
"Kinetic Ballooning Instabilities in NSTX"

1E29 C. S. Jones and P. J. Morrison
"Closures of the Vlasov-Poisson System"

Poster Sessions

1E30 Z. Lin
"Gyrokinetic Particle Simulation of Spectral Cascade and Energy Dissipation in Magnetohydrodynamic Turbulences"

1E31 V. S. Lukin, A. H. Glasser, and X. Z. Tang
"Development of the SEL code and its application to the magnetic reconnection problem"

1E32 A. Y. Pankin, I. Voitsekhovitch, G. Bateman, A. Dnestrovski, G. Janeschitz, A. H. Kritz, M. Murakami, T. Onjun, T. Osborne, G. W. Pacher, and H. D. Pacher
"Justification of the model for H-mode pedestal and ELMs"

1E33 R. Sanchez, B. Ph. van Milligen, and B. A. Carreras
"Nonlinear Generalized Master Equations: building a mathematical formalism to describe transport in the presence of critical thresholds"

1E34 B. N. Breizman, M. V. Fomyts'kyi, A. V. Arefiev, and C. Chiu
"Nonlinear physics of laser-irradiated micro-clusters"

1E35 L. Guazzotto, R. Betti, and J. P. Freidberg
"Progress towards the development of a linear MHD stability code for axisymmetric plasmas with arbitrary equilibrium flow"

1E36 E. V. Belova, R. C. Davidson, H. Ji, M. Yamada, C. D. Cothran, M. R. Brown, and M. J. Schaffer
"Numerical Study of the Formation, Ion Spin-up and Nonlinear Stability Properties of Field-Reversed Configurations"

1E37 A. L. Garcia-Perciante, J. D. Callen, K. C. Shaing, and C. C. Hegna
"Dynamic Parallel Viscous Force in the low collisionality regime"

1E38 P. J. Catto and A. N. Simakov
"Drift Ordered Short Mean Free Path Fluid Equations"

1E39 W. Ferenbaugh, D. E. Newman, and P. W. Terry
"Dynamics in Time Series: Characterization and Construction"

1E40 J. C. Wright, P. T. Bonoli, C. K. Phillips, M. Brambilla, and E. D'Azevedo
"An analysis of lower hybrid wave diffraction and focusing with a 2D toroidal full-wave code"

1E41 F. L. Waelbroeck and P. J. Morrison
"Hamiltonian description of ITG dynamics and coherent structures"

1E42 M. Kotschenreuther, J. Wiley, and L. Zheng
"Plasma Beta Enhancement in Reactors from the Thick Conducting Blanket"

Poster Sessions

1E43 M. K. Addae-Kagyah and E. D. Held
"Generalized Parallel Ion Viscous Stress Tensor in Slab Geometry"

1E44 J. H. Kim and W. Horton
"Multi-Scale Simulations of ITG and ETG with Sheared Flows"

1E45 D. A. Spong
"Neoclassical Parallel Momentum Balance and Flow Damping in Quasi-Symmetric Stellarators"

1E46 A. H. Glasser and A. N. Simakov
"Computation of Singular MHD Instabilities with DCON"

1E47 D. J. Strickler, D. del-Castillo-Negrete, and S. P. Hirshman
"Control and Optimization of the Vacuum Field Configuration in Compact Stellarators"

1E48 B. Hu, L. Guazzotto, and R. Betti
"Quasi-omnigenous tokamak equilibria with fast poloidal flow"

1E49 J.J. Ramos
"Collisionless axisymmetric equilibrium with diamagnetic flows"

1E50 J. Seol and C. C. Hegna
"Nonlinear wave-particle interaction in helically symmetric stellarators with bumpy fields"

1E51 X. Q. Xu and W. M. Nevins
"Development of a Gyro-kinetic Vlasov Simulation Code for Boundary Plasmas"

1E52 D. E. Newman, B. A. Carreras, and P. W. Terry
"Separate Dynamic Formation, Evolution and Control of Electron Channel Transport Barriers and Ion Channel Barriers"

1E53 J. Chen, G. Y. Fu, J. Breslau, and W. Park
"Hybrid Simulations of Alpha Particle effects on the Interal Kink Mode in ITER"

Poster Sessions

Poster Session 2C
Tuesday, April 27, 10:00 to 12:00, Lewis & Clark Ballrooms

2C01 D. Maslovsky, A. Boozer, M. Shilov
"Analysis of the Resistive Wall Mode Experiments in HBT-EP"

2C02 M. J. Mithaiwala and W. Horton
"Substorm Energetic Electron Injection Flux from a Dipolarization Model"

2C03 L. Chen and F. Zonca
"Kinetic Stability Analysis and Collisionless Damping of Zonal Flows"

2C04 H. Tian and C. R. Sovinec
"Semi-implicit Treatment of the Hall Term in NIMROD"

2C05 D. W. Ross and W. Dorland
"Further investigations of electromagnetic gyrokinetic simulation of plasma turbulence"

2C06 P. H. Diamond, K. Itoh, S.-I. Itoh, and T. S. Hahm
"Granulation Formation and Turbulent Trapping in Wave Kinetics"

2C07 C. C. Hegna and C. B. Forest
"Stabilization of Line Tied Resistive Wall Kink Modes Using Rotating Walls"

2C08 E. Kim and P. H. Diamond
"New Results on the Theory Anomalous Transport Reduction by shear: Mean shear and zonal shears"

2C09 R. Ball
"Singularities and bifurcations in models for L–H transitions"

2C10 T. G. Jenkins and W. W. Lee
"Collisional effects in gyrokinetic particle simulation"

2C11 C. R. Sovinec, G. A. Cone, and B. I. Cohen
"Integrated Modeling of Spheromak MHD and Energy Transport"

2C12 H. Tasso and G. N. Throumoulopoulos
"Lyapunov stability of certain MHD systems"

2C13 J. Carlsson
"Particle-in-Cell Simulations of ICRF Wave-Particle Interaction"

Poster Sessions

2C14 D. Westerly, A. S. Ware, R. Sanchez, L. A. Berry, G. Y. Fu, S. P. Hirshman, J. F. Lyon, D. A. Spong, and D. J. Strickler
"Impact of field line label and ballooning parameter on infinite-n ballooning stability in compact stellarators"

2C15 J. M. Finn, R. A. Nebel, and C. G. Bathke
"Single Helicity and Quasi-Single Helicity States in Reversed Field Pinches"

2C16 J. Preinhaelter, V. Shevchenko, M. Valovic, H. R. Wilson, P. Pavlo, L. Vahala, G. Vahala, and J. Urban
"Mode Conversion Processes to attain Electron Cyclotron Emission in Spherical Tokamaks"

2C17 H. E. Mynick, A. H. Boozer
"The interaction of neoclassical and turbulent transport in toroidal systems"

2C18 G. Vahala and L. Vahala
"Entropic Lattice Boltzmann Schemes"

2C19 C. Schleif, G. Vahala, L. Vahala, and A. I. D. Macnab
"Implicit Lattice Boltzmann Schemes"

2C20 C. Crabtree and L. Chen
"Finite gyroradius effects on drift compressional modes in very high beta plasmas"

2C21 B. K. Shivamoggi and N. Al-Salti
"Electron-inertia Effects on Driven Magnetic Field Reconnection"

2C22 A. V. Arefiev and B. N. Breizman
"Plasma detachment in a magnetic nozzle"

2C23 M. F. Salvetti and B. Coppi
"The Columbus Experiment"

2C24 W. X. Wang, Z. Lin, S. Ethier, J. L. V. Lewandowski, T. S. Hahm, W. W. Lee, G. Rewoldt, J. Manickam, and W. M. Tang
"Gyrokinetic Simulation of Microinstabilities in Generalized Toroidal Geometry"

2C25 H. V. Wong, W. Horton, and M. J. Mithaiwala
"Mirror Mode Analysis for Magnetic Depressions in the Solar Wind"

2C26 K. Hallatschek
"Turbulent saturation of tokamak core zonal flows"

2C27 C. Estrada-Mila, J. Candy, and R. E. Waltz
"Gyrokinetic Simulations of Plasma Transport and Isotope Effects"

Poster Sessions

2C28 B. Coppi, V. Roytershteyn, and C. Yarim
"Magnetic Reconnection and Intrinsically Associated Thermal Energy Transport"

2C29 A. N. Kaufman, A. J. Brizard, and E. R. Tracy
"Helicity in two-dimensional cold-plasma linear mode conversion"

2C30 R. Lionello, D. D. Schnack
"MHD Numerical Simulations on Tetrahedral Grids with MH4D"

2C31 M. A. Malkov and P. H. Diamond
"L-H transitions and transport barrier propagation in a simple model of coupled heat and particle fluxes"

2C32 P. B. Parks and L. R. Baylor
"Effect of Toroidicity on Fast Fuel Relocation in Tokamaks"

2C33 J. Sauer, A. S. Ware, D. E. Newman, P. W. Terry, and M. H. Hitchman
"Impact of Shear Flow on Turbulent Transport in a Neutral Fluid"

2C34 J. Breslau, W. Park, H. Strauss, L. Sugiyama, J. Chen, and S. Jardin
"MHD stability of low-n modes in small aspect ratio tokamaks"

2C35 S. Gupta, J. D. Callen, and C. C. Hegna
"Nonlinear Evolution of Magnetic-Shear Localized Interchange Instabilities"

2C36 F. Bombarda, B. Coppi, P. Detragiache, M. Romanelli
"Transport in High Density Igniting Plasmas"

2C37 P. Geren and L. Steinhauer
"Spectral modeling of nonlinear plasma evolution in compact toroids"

2C38 L. Chacón and D. A. Knoll
"A fully implicit 3D MHD Newton-Krylov algorithm: a numerical proof-of-principle"

2C39 R. Fitzpatrick
"Two-fluid magnetic reconnection with arbitrary guide-field"

2C40 A. Wurm and P. J. Morrison
"Action Principle Derivation of Reduced Fluid Models"

2C41 R. E. Waltz, J. Candy, and F. L. Hinton
"Gyrokinetic Simulations of Neoclassical Flows Embedded in Turbulence"

2C42 S. E. Kruger and D. D. Schnack
"Heat Flux Transport in Stochastic Magnetic Fields with Line Tying"

Poster Sessions

2C43 A. Airoldi, G. Cenacchi, and B. Coppi
"Onset of the thermonuclear instability and Oscillatory States near Ignition"

2C44 J. C. Kniep, J.-N. Leboeuf, and V. K. Decyk
"Gyrokinetic Particle-In-Cell Calculations of Ion Temperature Gradient Driven Turbulence with Parallel Nonlinearity and Strong Flow Corrections"

2C45 G. M. Staebler, J. E. Kinsey, and R. E. Waltz
"A Gyro-Landau-Fluid Model for Trapped and Circulating Particles"

2C46 B. Goode, J. R. Cary, and L. A. Berry
"Plasma Response to Waves in Arbitrary Magnetic Field Geometry"

2C47 Z. Sun, A. K. Sen and R. W. Longman
"Adaptive Optimal Control of RWM in Tokamak"

2C48 S. Hu and L. Chen
"Radial Localization and Energetic-Particle Excitation of Alfven-Ballooning Eigenmodes in High-Beta Toroidal Plasmas"

2C49 A. B. Rechester and R. B. White
"Symbolic Stability Analysis of Turbulent Fluctuation Data"

2C50 B. A. Shadwick, G. M. Tarkenton, and E. H. Esarey
"Thermal Effects in Intense Laser-Plasma Interactions"

2C51 G. Yu and S. I. Krasheninnikov
"On mesoscale plasma pressure perturbations in tokamak"

2C52 C. N. Nguyen, G. Bateman, A. H. Kritz
"Simulations of Saturated Tearing Modes in Tokamaks"

2C53 L. LoDestro, T. D. Rognlien, M. V. Umansky, X. Q. Xu, and R. H. Cohen
"Edge-plasma turbulence simulations with self-consistent profile evolution"

Monday morning, April 26

8:30 to 9:30

Doubletree Ballroom

Review Talk 1A

1A01

Climate Change: What Do We Really Know?

Inez Fung
University of California, Berkeley
inez@atmos.berkeley.edu

Changes in atmospheric composition lead to changes in the radiative forcing of the Earth. We review the greenhouse effect and the effect of aerosols on climate, and present the evidence for contemporary changes in radiative forcing. Climatic response to the radiative forcing is, to the lowest order, tied to the hydrologic cycle and changes in the three-dimensional distributions of water vapor, cloud water, and ice. Increases in water vapor and decreases in ice cover act to amplify the radiative forcing, while the effects of clouds on climate depend on the horizontal and vertical distribution of the clouds. Aerosols alter not only the radiative forcing, but also the formation and lifetime of clouds. Uncertainties in projections of climate change will be presented.

Monday morning, April 26

9:30 to 10:00

Doubletree Ballroom

Oral Session 1B

1B01

Non-diffusive transport in plasma turbulence: a fractional diffusion approach

D. del-Castillo-Negrete, B.A. Carreras, and V.E. Lynch

Fusion Energy Division
Oak Ridge National Laboratory
Oak Ridge, TN. 37831-6169

Recent experimental and theoretical evidence indicates that transport in magnetically confined fusion plasmas deviates from the standard diffusion paradigm. Typical examples include the confinement time scaling in low confinement mode plasmas, perturbative experiments, and the non-Gaussianity and long-range correlations of fluctuations. The standard diffusion paradigm breaks down in these cases because it rests on restrictive assumptions including locality (i.e., Fick's law), Gaussianity, lack of long-range correlations, and linearity. The need to develop models that go beyond these restrictive assumptions, is the main motivation of this presentation that has two connected goals. The first goal is to show numerical evidence of non-diffusive transport of test particles in plasma turbulence. Based on these turbulent transport calculations, our second goal is to propose and test a macroscopic transport model for non-diffusive transport using fractional derivative operators [1]. To accomplish these goals, we integrate test particles in the **E**×**B** field obtained from a nonlinear, three-dimensional, pressure-gradient-driven turbulence model. In this system, changes in the pressure gradient trigger instabilities at rational surfaces that locally flatten the pressure profile and increase the gradient in nearby surfaces. This in turn, leads to successive instabilities and intermittent transport which causes anomalous diffusion [2]. We show that the probability density function (pdf) of particles is strongly non-Gaussian and exhibits algebraic tails. Also, the moments of the particles' displacements exhibit super-difussive scaling $\langle \delta x^n \rangle \sim t^{n\nu}$ with $\nu > 1/2$.The proposed macroscopic model is based on the use of fractional derivative operators in space and time. The model incorporates in a unified way non-Gaussianity, and space-time non-locality (i.e., non-Fickian transport) caused by the presence of long-wainting times, and large-spatial displacements (Levy flights) without a characteristic scale. These effects can have non-trivial consequences in transport. For example, Levy flights can lead to asymmetric, exponential acceleration of fronts [3]. Here we shown that the fractional model reproduces the shape and spatio-temporal scaling of the pdf obtained from the turbulence calculation. In particular, quantitative agreement is found for the exponents of the algebraic decaying tails of the pdf, and the super-diffusive scaling exponent.

[1] del-Castillo-Negrete D., B.A. Carreras, and V.E. Lynch, submitted to Phys. Rev. Lett. (2004).
[2] Carreras B.A., V.E. Lynch, *et al.*, Phys. Plasmas **8**, 5096 (2001).
[3] del-Castillo-Negrete D., B.A. Carreras, and V.E. Lynch, Phys. Rev. Lett. **91**, 018302-1 (2003).

Monday morning, April 26

10:00 to 12:00

Lewis & Clark Room

Poster Session 1C

1C01

Simulation of MSE signals, as a diagnostic tool for MHD instabilities

J. Manickam, R, Jayakumar[1] and M. Okabayashi
Princeton Plasma Physics Laboratory
Box 451, Princeton N.J. 08543
[1]Lawrence Livermore National Laboratory
7000 East Ave., Livermore, CA 94550-9234

Mode identification of MHD instabilities is often based on external signals, typically, by Mirnov loops placed at some distance from the plasma. With a sufficient number of coils it is possible to identify the dominant poloidal and toroidal harmonics at the plasma boundary. The internal structure can be determined from the electron cyclotron emission[a]. Recently[b], the motional Stark effect, MSE, diagnostic has proved to be a complementary alternative, as it measures the local field perturbation within the discharge. The predicted mode structure for global instabilities is easily obtained from codes, such as PEST, from which, we can simulate the expected MSE signal. We examine a variety of plasma pressure and safety-factor profiles and geometry to determine the expected MSE signal. Comparisons with experiment will be presented.

This work supported by US Department of Energy under contract No. DE-AC02-76-CHO-3073

[a]Okabayashi et al. Nuclear Fusion Vol. 38, (1998) 1149

[b]Jayakumar et al. BAPS Vol. 48(2003) QP1.045

1C02

Dynamic Sub-Grid Scale Modeling of Tearing Mode Interaction with Turbulence

C. McDevitt and P.H. Diamond

University of California, San Diego,

Department of Physics, La Jolla, CA 92093-0319 USA

The development of the tearing mode instability is significantly affected by the existence of anomalous dissipation resulting from small-scale turbulence. Using the scale separation between the micro-turbulence and the large-scale fields associated with the tearing mode, a multi-scale analysis has been applied to the reduced resistive MHD equations yielding a set of wave-kinetic equations describing the evolution of small scale MHD turbulence in the presence of large scale fields and flows. Both the effect of the turbulence on the tearing mode and the back-reaction of large-scale fields on the turbulence are treated self-consistently. Application to the description of the single helicity state of the RFP is considered. In particular, the single helicity state requires both turbulent momentum transport and turbulent heat transport (due, in all likelihood, to ambient mirco-instabilities) for self-maintenance.

Equilibrium reconstraction and tokamak simulations with ESC-ASTRA[1]

L. E. Zakharov[1], S. N. Gerasimov[2], G. V. Pereverzev[3]

[1]*Princeton University, PPPL Princeton, NJ,*

[2]*JET IFDA, Culham, UK,* [3]*IPP, Garching, Germany*

February 27, 2004

Equilibrium reconstruction capabilities with use of raw data from JET have been recently implemented in the Equilibrium and Stability Code (ESC). thus. allowing self-consistent simulation of equilibrium. stability and transport (typically separated).

Four codes ESC-ASTRA-DCON-BALLOON assembled in a functional package with comprehensive (and uniform) run control, instantaneous access to the On-Line Help and Data-Base organization of IO. The ESC-ASTRA tandem works in the "code talking" regime with on-the-fly test of stability using DCON and BALLOON codes.

A compact, comprehensive and easy to generate output of equilibrium codes, called Equilibrium Spline Interface (ESI), has been developed and implemented for ESC-ASTRA communications. This interface provides necessary and sufficient data to reconstruct information on equilibrium for transport. MHD stability. gyro kinetic and particle orbit codes.

1C04

A comprehensive look at saturation dynamics of trapped electron mode turbulence

P.W. Terry, R. Gatto, and D.A. Baver
University of Wisconsin-Madison, Madison, Wisconsin 53706

Abstract

Comprehensive spectral analysis of trapped electron mode turbulence reveals that it does not saturate according to the canonical picture of quasi homogeneous, unstable plasma turbulence. It does not saturate by spectral energy transfer from unstable to stable modes, as identified by linear stability theory, and fluctuations carrying the energy do not have a frequency given by the unstable root of the linear dispersion relation. Instead, saturation is achieved by energy transfer to fully damped eigenmodes, i.e., roots of the dispersion relation that are damped for all wavenumbers $-\infty < k < \infty$. The excitation of such eigenmodes to finite amplitude causes wavenumbers that are unstable in linear analysis to become robustly stable at finite amplitude, making the landscape of linear sources and sinks a non predictor of energy transfer. Energy transferred to the damped eigenmode cascades to long wavelengths, even when the only nonlinearity is electron density advection. Inverse transfer is the result of near-resonant wave triads and reflects the wave anisotropy, while violating the doctrine that cascade direction is determined by dynamical invariants. The anisotropy of the inverse energy transfer process favors the excitation of zonal modes, including those of the damped eigenmode spectrum, opening a potent finite-amplitude-induced sink. These results are established for the weakly collisional (collisionless) limit of a fluid model for trapped electron mode turbulence,[1] using bispectral analysis of simulation results, analysis of the basic symmetries of the model, and an analytical solution of the statistical closure equations in the strong-turbulence limit. The latter is made possible by an asymptotic expansion, and yields the nonlinear frequencies and saturation levels of density, potential, and density-potential cross power for both the turbulence spectrum and zonal modes. Like other systems with coupling to zonal modes, the system first saturates at a relatively high level, and then adjusts to a lower level as the zonal modes increase relative to non zonal modes. When zonal mode coupling is removed, the turbulence level increases by at least an order of magnitude. Analysis shows that this is caused by the removal of the saturation channel associated with anisotropic spectral transfer to the zonal modes of the damped eigenmode root, and has nothing to do with E×B shearing. Indeed, the E×B shearing rate cannot exceed the nonlinear correlation rate, consistent with recent observations from beam emission spectroscopy in DIII-D.[2]

[1]P.W. Terry, R. Gatto, and D.A. Baver, Phys. Rev. Lett. **89**, 205001 (2002).
[2]M. Jakubowski, Ph.D. Thesis, University of Wisconsin-Madison, 2003.
Work supported by USDOE.

1C05

Predicting Ideal MHD Stability From Perturbed Equilibria: Successful Wall Perturbations and Limitations from Compressional Alfvén Energy[1]

K.J. Comer[2], J.D. Callen, C.C. Hegna (U. of Wisconsin, Madison),
A.D. Turnbull (General Atomics), S.C. Cowley (Imperial College/UCLA)

The effects of equilibrium parameters on long wavelength ideal MHD instabilities in toroidal plasmas are traditionally studied using numerical parameter scans. Previously, we introduced a new perturbative technique to explore these dependencies: changes in the potential energy δW due to small equilibrium variations are calculated using a perturbation of the energy principle, rather than with an eigenvalue-solver instability code.

With this perturbed equilibrium approach, stability dependencies can, in principle, be quickly determined without numerically generating complete MHD stability results for every set of parameters (which can be time-intensive for accurate representations of several configurations). Compared to a routine parameter scan, this approach may also provide the researcher a more intuitive feel for the effects of various parameters.

Previous applications of this approach to toroidal geometry used GATO (an ideal MHD stability code) and both experimental and simplified equilibria. Experimental analysis focused on DIII-D shot 87009, which exhibits global internal n=1, m=2 and m=3 kink modes. This technique was expected to work well with global modes; however, changes more than only $\sim 0.1\%$ to q_o or β predicted δW several orders of magnitude too large. Perturbing the simple equilibria (circular cross-section, $\beta = 0$ and $1 < q < 2$) gave similar results: allowable perturbations in aspect ratio A were also limited to only $\sim 1\%$.

We first briefly review the perturbed stability analysis for a cylindrical circular equilibrium, which works well with this approach. We also review results from DIII-D shot 87009 and the simple equilibria, which are valid only over a small range of most perturbations. Wall parameters are an exception, and we show instances where wall distance and shape *do* tolerate significant variation. The unexpected sensitivity to equilibrium (rather than wall) perturbations is due to the compressional Alfvén contribution to δW. Beyond a very small range of perturbations, second order terms in the expansion of compressional Alfvén energy become large. We explore methods of ameliorating these second order terms.

---

[1]Research supported by US DOE Contract DE-FG02-92ER54139.
[2]comer@cae.wisc.edu, 520 Engineering Research Building, 1500 Engineering Dr., Madison, WI 53706-1609

1C06

Physics of Plasma Accretion Disks

[1]P.S. Coppi and [2]B. Coppi

[1]Yale University, New Haven, CT
[2]Massachusetts Institute of Technology, Cambridge, MA

In plasma accretion disks from which jets can emerge it is reasonable to consider physical regimes where the magnetic field energy can be of the order of the thermal energy ($\beta \sim 1$).
The axisymmetric magnetic and electric field configurations that can be present in thin disks in different β regimes is discussed. Two-dimensional modes, that can be excited from axisymmetric equilibrium disk configuration have to be of the ballooning kind [1] in the vertical direction and have an intrinsic difficulty in fitting into the height of the disk [2] unless β is relatively large and then have insufficient growth rates to produce the rates of transport of angular momentum that are needed to explain the luminosities of a significant variety of objects. Conversely, bending (tridimensional) modes that are singular when described by the linearized ideal MHD approximation can be excited and lead to substantial outward fluxes of the angular momentum corresponding to significant rates of accretion. However, these modes and their growth rates depend on the nonlinear processes that make the transition across the ideal MHD singularities possible. A broad class of non linear equations that can be suitable for this is identified. The considered modes are localized around the radius where they co-rotate with the disk and the singularities correspond to the radii where the relevant Doppler shifted frequency becomes equal to the slow magnetosonic frequency and to the shear Alfvén wave frequency[1].

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

[1] B. Coppi and P.S. Coppi, Phys. Rev. Letters **85**, 5, 051101-1 (2001)
[2] B. Coppi and E.A. Keyes, Ap. J. **595**, 1000 (2003).

1C07

The Complete Set of Casimir Constants of the Motion in Magneto-Hydrodynamics*

Elie Hameiri
Courant Institute of Mathematical Sciences, NYU,
251 Mercer St., New York, NY 10012

Abstract

MHD is a Hamiltonian system, the evolution of which can be given a non-canonical formulation with the use of a Poisson bracket involving only Eulerian variables of the plasma fluid.[1] Casimirs are functionals for which the bracket vanishes, regardless of which Hamiltonian function is used (even non-MHD). In particular, they also constitute constants of the motion for the MHD system.

The practice so far has been to find Casimirs by formulating a variational principle for the plasma evolution, typically a Lagrangian integral using Lagrangian variables of the fluid, and to apply Noether's theorems. This procedure is problematic in a number of respects: 1. Not every Hamiltonian system has a natural Lagrangian integral; 2. The Noether approach is complicated to carry out and one does not know if all constants of the motion were found; 3. Casimirs arise in the Eulerian description and form a special class of constants of the motion, easier to find than other conserved quantities, so their special properties should be used.

Our approach is to derive from the Poisson brackets a set of functional equations all Casimirs need to satisfy. We then determine the general solution of the spatial dependence of the various functional derivatives involved. From this, a limited number of *possible* forms of every Casimir can be found. A direct check pinpoints the Casimirs. We get a full set of the Casimirs for a configuration with nested magnetic flux surfaces, as well as other configurations (which have many fewer Casimirs). We identify one velocity-dependent Casimir which exists in all configurations and can help improve a classical stability criterion.[2]

*Work supported by US Department of Energy Grant No. DE-FG02-86ER53223.

1. P. Morrison and J. Greene, Phys. Rev. Lett. **45**, 790 (1980).

2. E. Frieman and M. Rotenberg, Rev. Mod. Phys. **32**, 898 (1960).

1C08

Axisymmetric Modes in Thin Accretion Disks: Limits on β

E.A. Keyes, B. Coppi

Massachusetts Institute of Technology
Cambridge, MA 02139

Abstract

A central problem in the study of accretion disks is the process by which angular momentum is transported outward at a rate sufficient to explain the observed luminosity of accretion-powered astronomical sources, which is far higher than conventional gas viscosities can account for. Current research focuses on plasma-physics instabilities, since conditions around accreting objects are likely to consist of ionized, magnetized material whose viscosity is dominated by collective modes rather than collisions.

In particular, one possibility that has been considered relies on axisymmetric modes such as the Magneto-Rotational Instability[1,2] to generate an effective viscosity through the excitation of turbulence in the disk. These modes use magnetic fields to couple matter orbiting with relative velocities in a differentially-rotating plasma, and were originally derived for the case of long-cylinder geometry. However, our previous work[3] showed that when vertically confined in a thin accretion disk due to a density profile across the height of the disk, the MRI modes become of the ballooning type instead, with radial oscillations, reduced growth rates, and strong limitations on the magnetic field strengths compatible with their excitation.

We review the relevant analytical approaches and expand our previous results with numerical studies of the axisymmetric modes to identify the limits on β, the ratio of the magnetic energy density to the plasma pressure, above which marginally-stable modes and unstable modes disappear. The present state of our analysis confirms our conclusions given in Ref. 3, that unstable axisymmetric modes in thin accretion disks require quite low values of the magnetic pressure relative to the plasma pressure and have growth rates that are insufficient[4] to provide the rate of momentum transport needed to explain the luminosities of a significantly large variety of objects.

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

[1] Velikhov, E.P., *Soviet Phys.–JETP* **36**:995 (1959).
[2] Balbus, S.A. and Hawley, J.F., *ApJ* **376**:214 (1991).
[3] Coppi, B. and Keyes, E.A., *ApJ* **595**:1000 (2003).
[4] Coppi, B. and Coppi, P.S., *Phys. Rev. Letters* **85**, 5, 051101-1 (2001).

1C09

Reconnection studies using a collisionless fluid closure model

A. Y. Aydemir[1] and J. J. Ramos[2]

[1] *Institute for Fusion Studies, The University of Texas at Austin Austin, TX 78712*
[2] *Plasma Science and Fusion Center, MIT, Cambridge MA 02139*

We study driven reconnection in a quadrupole field geometry using a collisionless magneto-fluid closure model recently derived by one of us[1]. The two-fluid model uses an anisotropic pressure tensor with independent evolution equations for the parallel and perpendicular pressures and heat fluxes. For our reconnection studies, the model equations are augmented, in the cold-ion limit, with a generalized Ohm's law of the form

$$\mathbf{E} = -\mathbf{u}\times\mathbf{B} + \frac{1}{en}\left(\mathbf{J}\times\mathbf{B} - \nabla p_{e\perp} - \mathbf{b}(\mathbf{b}\cdot\nabla)(p_{e\parallel} - p_{e\perp})\right) + \eta\mathbf{J}.$$

These results will be compared with those from a Hall-MHD model using an isotropic electron pressure with an isothermal equation of state, and also with simple reduced resistive MHD.

[1] J. J. Ramos, Phys. Plasmas **10**, 3601 (2003).

1C10

Spheromak Formation by Steady Inductive Helicity Injection in 3D MHD Simulations

V.A. Izzo, T.R. Jarboe, P.E. Sieck

University of Washington
Seattle, WA 98195

Abstract

The HIT-SI spheromak, which began operation in 2003, is formed and sustained by a novel means known as Steady Inductive Helicity Injection (SIHI). The device geometry consists of the bow-tie spheromak confinement region and two half toroids which serve as the injectors. Each injector is operated by two coils producing a 5kHz oscillating flux and loop voltage. While the initial stage of the experiment has focused on studies of the injector operation, 3D numerical simulations with the NIMROD code have produced initial results concerning spheromak formation in the confinement region. In the simulations, the injectors are replaced with non-symmetric boundary conditions on the confinement region. Each simulation begins with no magnetic field in the volume, and the SIHI drive ramps up over one cycle (0.2ms), then holds a constant amplitude for two cycles and finally ramps down over one cycle, after which the remaining equilibrium is allowed to briefly further evolve. Computational resources limit the pulse length, which is tens of cycles in the experiment. Because of the predominantly n=1 symmetry of the SIHI injector fields, they are easily distinguishable from the equilibrium fields in magnetic energy spectra of the computational results. At a small Lundquist number, comparable to the initial operating phase of the experiment, the n=0 (equilibrium) magnetic energy remains considerably smaller than the n=1 (injector) energy during the sustained phase. As the injectors ramp down, the injector fields are forced to reconnect in the volume, causing a rise in the equilibrium amplitude at the end of the pulse. The equilibrium then decays once the drive has ceased completely. When the plasma resistivity is lowered to produce a moderate Lundquist number, the n=0 magnetic energy grows much larger than the n=1 energy during the sustained phase, supporting the expectation of observable spheromak formation on the HIT-SI device when hotter plasmas are created in the next experimental phase.

1C11

Application of the Spectral Element Code (SEL) to Edge Plasma Modeling*

Andrei N. Simakov, Alan H. Glasser, Vyacheslav S. Lukin, X. Z. Tang

Los Alamos National Laboratory
Los Alamos, NM 87544

Abstract

SEL [1] is a new massively-parallel implicit spectral element [2,3] code for macroscopic multidimensional modeling of magnetized plasma being developed at Los Alamos National Laboratory. It uses high-order spectral elements on a logically rectangular grid for spatial discretization and second-order adaptive implicit Newton-Krylov method for time-advancing. In this work a 2D version of SEL is used to solve a new system of drift-ordered short mean-free path two-fluid equations [4] to model a highly-turbulent plasma evolution in linear devices. This serves as the initial step towards using a 3D version of SEL with equations [4] for modeling tokamak edge plasma turbulence in a realistic geometry. Continuity, parallel Ohm's law, parallel total momentum, vorticity, electron and ion energy equations supplemented by equations for perturbed magnetic and electric fields are solved in a circular or annular domain with normal to it equilibrium magnetic field, which represents a linear machine cross-section. Interchange modes are considered. The linear stability is benchmarked against numerical solutions of the corresponding radial Sturm-Liouville problem. Formation of plasma "blobs" in the "bulk" plasma, their peeling off at the "separatrix" and radial propagation towards the wall due to the effects of "neutral wind" in the "scrape-off" layer [5] is studied.

[1] A.H. Glasser and X.Z. Tang, The SEL spectral element code, to appear in Comp. Phys. Comm. (2004).
[2] R.D. Henderson, in *Higher-Order Methods for Computational Physics*, edited by T.J. Barth and H. Deconinck (Springer, New York, 1999).
[3] G.E. Karniadakis and S.J. Sherwin, *Spectral/hp Element Methods for CFD* (Oxford University Press, New York, 1999).
[4] A.N. Simakov and P.J. Catto, Phys. Plasmas **10**, 4744 (2003).
[5] S.I. Krasheninnikov and A.I. Smolyakov, Phys. Plasmas **10**, 3020 (2003).

*Work supported by U.S. D.o.E.

1C12

Effects of particles with large gyroradii on magnetohydrodynamic stability

V. A. Svidzinski, S. C. Prager
Department of Physics, University of Wisconsin-Madison
Madison WI 53706

Abstract

Fast ions in tokamaks are known to have a significant influence on global plasma instabilities. In normal mode analyses for tokamaks, the perturbed electric and magnetic fields have been evaluated at the position of the particle's guiding center. We consider the effect of spatial variation of the perturbed fields *within* the gyroradius for internal magnetohydrodynamic (MHD) modes. We investigate the resulting tearing mode stability for the reversed field pinch (RFP) and the internal kink mode in tokamak. Such effects are important for neutral beam injected particles in current RFP experiments and for fusion-generated alpha particles or ion cyclotron frequency heated ions in tokamaks. The fast particle dielectric response is evaluated from the linearized Vlasov equation, and inserted into a cylindrical MHD model for the bulk plasma. In the initial model the response is found for a simplified particle distribution function assuming that the equilibrium magnetic field is uniform within the gyro-orbit. The effect of large gyroradii is strong, and can be either stabilizing or destabilizing (depending on the radial distribution of the fast particle density). The effect is maximal when the fast particles reside near the tearing-resonant surface. The outline of more accurate modeling (being developed now) will be presented.

1C13

Paleoclassical Electron Heat Transport In Toroidal Plasmas

J.D. Callen, University of Wisconsin, Madison, WI 53706-1609

An important new mechanism for radial electron heat transport has recently been identified [1,2]. It results from a combination of parallel free-streaming and the "paleocalassical" Coulomb collisional processes of parallel electron heat conduction and magnetic field diffusion in low collisionality toroidal plasmas. The key new physical point is that as magnetic field lines diffuse radially (with $D_\eta \equiv \eta/\mu_0 = \nu_e c^2/\omega_p^2$), they carry electron heat equilibrated over a long distance $2L$ along magnetic field lines. The parallel half-length L is the minimum of the electron collision length λ_e and a maximum effective field line length which is the minimum of the half-length of a low order rational field line ($2\pi R_0 q\, n^\circ$) or an electromagnetic-skin-depth- and magnetic-shear-determined length $\ell_{\rm max} \equiv \pi R_0 q\, n_{\rm max}$ in which $n_{\rm max} \equiv (\pi \delta_e q')^{-1/2}$ is a maximum toroidal Fourier harmonic number, $\delta_e \equiv c/\omega_p$ is the electromagnetic (em) skin depth and $q' \equiv dq/dr$. Since L is much longer than the poloidal periodicity half-length $\pi R_0 q$, the radial electron heat diffusivity is a multiple $M \equiv L/\pi R_0 q >> 1$ (typically $M \gtrsim 10$) times the magnetic field line diffusivity: $\chi_e^{\rm pc} \sim M\, \nu_e c^2/\omega_p^2$.

The evolution equation for the magnetic flux ψ is obtained from a combination of Faraday's and Ampere's laws using an Ohm's law that includes electron inertia:

$$(1-\delta_e^2\nabla^2)\,\frac{d\psi}{dt} = \frac{\eta_\parallel}{\mu_0}\nabla^2\psi - \frac{\partial\Psi}{\partial t}, \quad \text{with } \delta_e \equiv \frac{c}{\omega_p} \text{ (em skin depth) and } \frac{\partial\Psi}{\partial t} \equiv E_z^A. \qquad (1)$$

Here, E_z^A is the inductive toroidal electric field, which, in resistive equilibrium, balances the $\eta_\parallel$-induced magnetic field diffusion. When $\delta_e^2\nabla^2 << 1$ (i.e., for $x > \delta_c$) ψ and hence the magnetic field lines diffuse with a diffusion coefficient $D_\eta \equiv \eta_\parallel/\mu_0 \simeq \nu_e\delta_e^2 \sim (\Delta x)^2/\Delta t$, which implies diffusive steps $\Delta x = \delta_e$ in an electron collision time $\Delta t = 1/\nu_e$. For $x < \delta_e$ ($\ell_\parallel > \ell_{\rm max}$) the solution of (1) for ψ becomes spatially evanescent.

Radial transport of electron heat "contained" on diffusing magnetic field lines is calculated using a Chapman-Enskog approach [3]. In the paleoclassical model magnetic field diffusion occurs on the same time scale as parallel free-streaming and heat conduction of electrons. This effect is taken into account by transforming from a stationary coordinate system to one moving with the magnetic flux function ψ: $\partial/\partial t|_{\rm x} = \partial/\partial t|_\psi + \partial\psi/\partial t|_{\rm x}\partial/\partial\psi$, with $\partial\psi/\partial t|_{\rm x}$ from (1). Then, the kinetic equation for the kinetic distortion F away from a dynamic Maxwellian f_M has an additional $-\partial\psi/\partial t|_{\rm x}\partial f_M/\partial\psi$ "source" or drive term. To lowest order F and T_e are nearly constant along magnetic field lines [2] — electrons and their heat are frozen to the magnetic field lines and hence flux sufaces which, according to (1) with $\delta_e^2\nabla^2 << 1$, are diffusing.

The divergence of the conductive parallel electron heat flow induced by $\partial\psi/\partial t|_{\rm x} \neq 0$ in the presence of a radial electron temperature gradient is [1,2] $\nabla_\parallel q_{\parallel e} \simeq -[n_e/(2A_{01})]\partial\psi/\partial t|_{\rm x} dT_e/d\psi$ at all points along a magnetic field line whose effective length is $2L$. Integrating it from $-L$ to L and dividing by the field line poloidal periodicity length $2\pi R_0 q$ (due to the inverse ballooning transform [4] in axisymmetric toroidal geometry), the effective electron temperature evolution equation $(3/2)n_e dT_e/dt = -\langle\nabla_\parallel q_\parallel\rangle + \cdots$ becomes

$$\frac{3}{2}\frac{dT_e}{dt} = M\left(\frac{\eta_\parallel}{\mu_0}\nabla^2 T_e - E_z^A\frac{dT_e}{d\psi}\right) + (\chi_e^{\rm nc} + \chi_e^{\rm anom})\nabla^2 T_e + \frac{Q_e}{n_e} \quad \Longrightarrow \quad \chi_e^{\rm pc} \equiv M\frac{\eta_\parallel}{\mu_0} \sim \left(\frac{L}{\pi R_0 q}\right)\nu_e\frac{c^2}{\omega_p^2}. \quad (2)$$

This is a diffusion equation for the electron temperature T_e with a paleoclassical diffusion coefficient $\chi_e^{\rm pc}$; it relaxes a factor of M faster than ψ does. Usually $dT_e/d\psi < 0$ and the second term on the right in (2) is positive: it apparently causes the often-observed [5] electron "heat pinch."

The paleoclassical model of radial electron transport is in reasonable accord [1,2] with many features of "anomalous" electron heat transport, including: 1) Magnitude (e.g., $\chi_e^{\rm pc} \sim 2$ m^2/s for TFTR ohmic plasmas at $r/a \simeq 0.5$), 2) $\chi_e^{\rm pc}$ increases with r, 3) Alcator confinement scaling ($\propto n_e$) and magnitude, 4) Profile resiliency and larger transient than equilibrium transport (because the heat pinch partially cancels $\chi_e^{\rm pc}$ diffusion), and 6) Reduced transport and internal transport barriers at low order rational surfaces [6].

[1] J.D. Callen, "Electron Heat Transport Is Not Anomalous; It's A Paleoclassical Process In Toroidal Plasmas," submitted (February 2004) to Phys. Rev. Lett. (available at www.cae.wisc.edu/~callen).
[2] J.D. Callen, "Paleoclassical Transport Processes In Low Collisionality Toroidal Plasmas," in preparation.
[3] J.P. Wang, J.D. Callen, Phys. Fluids B 4, 1139 (1992); Z. Chang, J.D. Callen, Phys. Fluids B 4, 1167 (1992).
[4] R.D. Hazeltine and W.A. Newcomb, Phys. Fluids B 2, 7 (1990).
[5] J.D. Callen, J.P. Christiansen, J.G. Cordey, P.R. Thomas, and K. Thomsen, Nucl. Fusion 27, 1857 (1987).
[6] G.M.D. Hogeweij, N.J. Lopes Cardozo, M.R. de Baar, and A.M.R. Schilham, Nucl. Fusion 38, 1881 (1998).

Chandrasekhar equilibria of compact toroids with Alfvénic flows

Zhehui Wang and X. Z. Tang

Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract

The Chandrasekhar equilibria are a class of stationary ideal magnetohydrodynamic equilibria stabilized by magnetic-field-aligned Alfvénic flows against fixed-boundary ideal MHD modes with a solenoid-free perturbation in the displacement vector.[1] The basic idea of the Chandrasekhar equilibrium is to have the inertia of a field-aligned Alfvénic plasma flow balance the magnetic curvature force plus the parallel gradient of magnetic pressure,

$$\rho \mathbf{U} \cdot \nabla \mathbf{U} = \frac{1}{\mu_0} \mathbf{B} \cdot \nabla \mathbf{B}. \tag{1}$$

The overall force balance is then reduced to

$$\Pi \equiv p + B^2/2\mu_0 = constant, \tag{2}$$

for a steady state plasma. The stabilization effect of a field-line-aligned Alfvénic flow is not limited to ideal modes. For example, in the Chandrasekhar equilibrium of a Harris sheet, the Alfvénic flow is found to stabilize the resistive tearing modes.[2] Unlike the Grad-Shafranov equilibrium of a static plasma where two free functions (of magnetic flux), usually pressure and plasma current, are required to specify an equilibrium, the specification of a Chandrasekhar equilibrium admits total freedom in magnetic field design. For any specified $\mathbf{B}$, the plasma flow is solved from equation (1) and the corresponding plasma pressure is found from equation (2). Analytic Chandrasekhar equilibrium of FRC and spheromak can be elegantly solved[3] with Chandrasekhar-Kendall modes[4] from a field constraint of the form

$$\sum_n c_n \left(\nabla\times\right)^n \left(\mu_0 \mathbf{J}\right) = \lambda \mathbf{B}$$

where c_ns $(n = 0, 1, 2, \cdots)$ are constant coefficients and $(\nabla\times)^n \equiv \overbrace{\nabla\times\nabla\times\cdots\nabla\times}^{n}$. Favorable confinement property of nested closed flux surfaces and the unusual ideal magneto-hydrodynamic stability of such compact toroids are of interest for both magnetic trapping of high energy electrons in astrophysics and confinement of high temperature plasmas in laboratory. The similarity and important distinctions between Chandrasekhar compact toroid equilibria[3] and those predicted by relaxation theories[5] will be clarified. This work was supported by DoE OFES.

[1] S. Chandrasekhar, *Hydrodynamic and Hydromagnetic Stability*, (Dover, New York, 1981).
[2] L. Chacon, D.A. Knoll, and J.M. Finn, Physics Letters A, **308** (2003) 187.
[3] Z. Wang and X. Z. Tang, submitted to Phys. Plasmas (2003).
[4] S. Chandrasekhar and P. C. Kendall, Astrophys. J. **126**, 457 (1957).
[5] L. C. Steinhauer and A. Ishida, Phys. Rev. Lett. **79**, 3423 (1997); S. M. Mahajan, and Z. Yoshida, *ibid* **81**, 4863 (1998); B. Dasgupta, P. Dasgupta, M. S. Janaki, T. Watanabe and T. Sato, *ibid* **81**, 3144 (1998).

1C15

Alfvén Waves in Gyrokinetic Plasmas and Transport Time Scale Simulations*

W. W. Lee, S. Ethier, W. X. Wang
Princeton Plasma Physics Laboratory, Princeton, NJ 08540
Z. Lin
University of California, Irvine, CA 92697

We will report in this paper the properties of shear and compressional Alfvén waves in gyrokinetic plasmas.[1,2] One salient feature of these waves in comparison with their MHD counterparts is the role played by compressional Alfvén waves in magnetic field calculations. Specifically, we can eliminate these waves in gyrokinetic plasmas through frequency ordering while one needs further geometric simplifications or implicit numerical schemes in the MHD description for their suppression. We will focus on this unique property to design a scheme for simulating plasma turbulence and kinetic-MHD on the transport time scale using our global gyrokinetic particle simulation code (GTC) which has been utilized recently for turbulence simulations of reactor size plasmas.[3] The proposed scheme also depends critically on the concept of steady state turbulent transport using entropy production in the presence of collisionless and/or collisional dissipations as a measuring stick.[4,5] In this regard, we need simulation models that can properly take into account velocity space nonlinearities[6] and collisions that are momentum and energy conserving.[5,7] Both of these effects are already in place in the GTC code, where collisions are treated as subgrid phenomena using Monte-Carlo operations. The procedures for using GTC to simulate turbulence transport and kinetic-MHD physics, and to predict profile (density, current, pressure) evolution and to advance magnetic topology on the transport time scale will be discussed. The expected performance of such a code on MPP platforms, such as the cached-based Seaborg at NERSC and the vector-parallel Earth Simulator in Japan will be reported as well.

*Work is supported by US DoE and the SciDAC project.

[1] W. W. Lee et al., Phys. Plasmas **8**, 4435 (2001).
[2] W. W. Lee and H. Qin, Phys. Plasmas **10**, 3196 (2003).
[3] Z. Lin et al., Phys. Rev. Lett. **88**, 195004 (2002).
[4] W. W. Lee and W. M. Tang, Phys. Fluids **31**, 612 (1988).
[5] Z. Lin et al., Phys. Plasmas **7**, 1857 (2004).
[6] T. S. Hahm, Phy. Fluids **31**, 2670 (1988).

(Oral Talk)

On the Electric Pedestal

F. W. Perkins

Princeton DIII-D Collaboration
Princeton Plasma Physics Laboratory
PO Box 451
Princeton, NJ 08543

Abstract

This contribution examines an often-overlooked aspect of pedestal physics — the maintenance of over-all charge neutrality in the presence of ion loss arising from finite- banana width departures from closed flux surfaces. A negative radial electric field E_r' and current density $j_r = \sigma_\perp E_r'$ build up to assure that the total current remains divergence-free. Here, E_r' is to be evaluated in the frame rotating with the plasma and $\sigma_\perp$ is a neoclassical conductivity called the orthogonal conductivity. The argument for the orthogonal conductivity is straightforward. Let us suppose a non-ambipolar process has induced a radial electric field E_r' in the plasma in addition to the electric field associated with a general toroidal rotation. In response to this field, the trapped ions execute a toroidal processional drift $v_\phi = E_r' c/B_\theta$. Through ion-ion collisions, these particles exert a toroidal acceleration on the bulk plasma given by

$$F_\phi = n_t M \frac{E_r c}{B_\theta} v_{ii} = n M R \frac{d\Omega}{dt} \qquad (1)$$

where Ω denotes the circulating ion toroidal rotation rate. The corresponding azimuthal drag force on the precessing trapped particles gives rise to a generalization of the Ware pinch with $F_\phi / n_t e$ replacing E_ϕ . The pinch velocity is

$$v_r = \frac{M E_r v_{ii} c^2}{e B_\theta^2} = \left(\frac{F_\phi}{e n_t}\right)\frac{c}{B_\theta} \qquad \text{and} \qquad j = n_t e v_r = f_t \frac{n e^2 v_{ii}}{M \Omega_\theta^2} E_r = \sigma_\perp E_r \qquad (2)$$

where f_t is the fraction of trapped ions. The model further supposes that ions are electrostatically confined and in thermal equilibrium. Consequently, density and potential variations are coupled via $n_i \propto \exp(-e\Phi/T)$; any density variation has a potential variation and E_r'. The rate of ion orbit loss, which drives the system, is controlled by the rate at which an ion can, by energy diffusion, exceed the confining electrostatic potential. This rate, too, depends on the potential through the density. All these elements can be combined into a second order differential equation, which supports spontaneous development of high gradient regions. The electrostatic, thermal-equilibrium confinement model implies an isotropic velocity distribution for the ions and consequently ions have no net velocity or contribution to bootstrap currents, which are carried instead by electrons.

*Work supported by U.S. Department of Energy under Contract DE-AC02-76CH03073

1C17

Enhanced Neoclassical Polarization, Zonal Flow Suppresion and Elevated Turbulence in Tokamaks

Kim Molvig, Yong Xiao, Darin R. Ernst, Klaus Hallatschek
Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139

Abstract

Simulations[1] of ion temperature gradient (ITG) turbulence in tokamaks show a strong saturating effect from zonal flows driven by the turbulence. The effectiveness of this saturation mechanism has been attributed to the linearly undamped nature of the zonal flows as first discussed by Rosenbluth and Hinton [2] in the collisionless regime. Although much of the attention has focused on the zonal flows, it is actually the neoclassical polarization that determines the effectiveness of the zonal flow shearing in saturating the turbulence. The smaller the polarization the larger will be the zonal flow response which leads to the relatively small saturated turbulence levels observed in simulations. Several neoclassical polarization regimes are present depending on collisionality. The low frequency, collisional, limit, is well known and is larger than the Rosenbluth, Hinton result by a factor of order, $\varepsilon^{-3/2}$. This limit of the zonal flow response is not present in any of the simulations, and looms as a concern. The zonal flow spectra observed peak at zero frequency where this collisional limit is clearly the correct polarization, not the Rosenbluth-Hinton value that is being achieved in the codes. It is not a simple matter to include collisions accurately enough to capture this effect, but the implications for turbulence simulations are serious. Underprediction of the neoclassical polarization will lead to underprediction of the turbulence level. We have also argued elsewhere (Sherwood Fusion Theory Meeting, 2003), that even at lower collisionality, the Rosenbluth-Hinton result is too small. This paper compares the various theories and makes suggestions for the simulation codes to help resolve what is an important question for tokamak turbulence.

[1] W. Dorland, F. Jenko, M. Kotschenruther, B.N. Rogers, Phys. Rev. Lett. **85**, 5579 (2000); R.E. Waltz, G.D. Kerbel, J. Milovich and G.W. Hammett, Phys. Plasmas, **2**, 2408 (1995); Z. Lin, T.S. Hahm, W.W. Lee, W.M. Tang and R.B. White, Science, **281**, 1835 (1998)

[2] M.N. Rosenbluth and F.L. Hinton, Phys. Rev. Lett. **80**, 724 (1998).

3D Reconnection: onset and topology

G. Lapenta, J.U. Brackbill, W. Daughton, P. Ricci
Plasma Theory Group (T-15), Los Alamos National Laboratory

Abstract

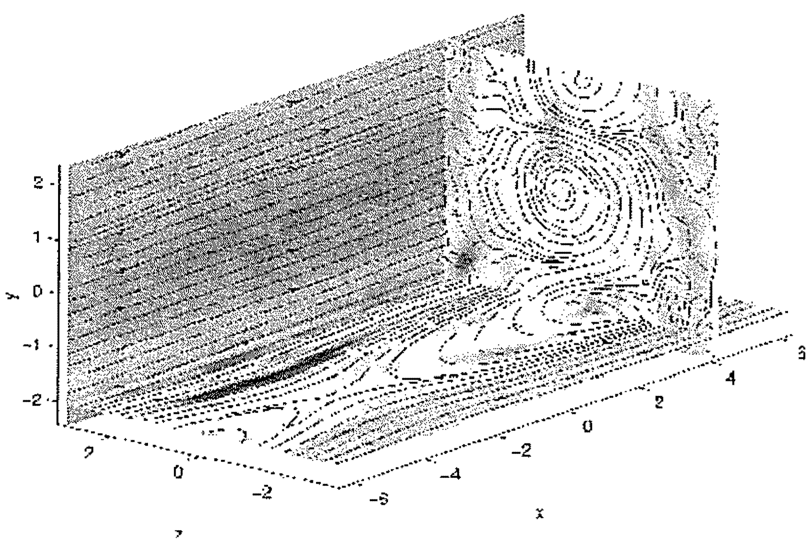
We study the stability and non linear behaviour of perturbations in a current sheet. Our tools are a kinetic linear code, explicit massively parallel PIC simulations and implicit PIC simulations. Three classes of instabilities are considered.

First, the tearing instability is observed to grow and cause reconnection as predicted by the linear theory. However, in accord with an early theoretical study, the tearing mode in 2D is observed to saturate at very low amplitude, too low to explain the onset of macroscopic magnetic reconnection observed in 3D simulations and in real plasmas. Furthermore, in presence of a magnetic field component orthogonal to the current sheet, the tearing instability is stabilized.

Second, modes propagating in oblique directions appear to be irrelevant in the cases considered.

Third, the true cause of the onset of reconnection is linked to the modes propagating in the current direction and particularly to the lower hybrid drift instability (LHDI). The LHDI is shown to cause 3 modifications of the initial Harris configuration: creation of a velocity shear, introduction of temperature anisotropy and thinning of the initial current profile. These effects offset the saturation and stabilization mechanisms of the tearing instability and allow reconnection to progress beyond the saturation level of the pure tearing mode.

The modifications induced by the LHDI cause a profound change of the topology and configuration of the reconnection region. An example of the reconnected configuration is shown in the figure below, where, besides the presence of a classic reconnection x-line, one can observe the presence of kinking in the y direction and a flux rope structure replaces the usual 2D plasmoid.



1C19

Electron Heat Confinement in Reversed Field Pinches *

J. W. James, E. D. Held
Physics Department, Utah State University
Logan, UT 84321-4415

Abstract

In this work, electron heat confinement times in reversed field pinches are predicted by calculating effective radial electron thermal diffusivities χ_{er} using various methods and compared to confinement times measured in experiments.

The first method derives the effective radial electron thermal diffusivity from the tangled nature of the magnetic field itself[†]. The relation of these stochastic diffusivities to the Lyapunov spectrum of the magnetic field is explored. Stochastic diffusivities are compared to those calculated directly from the component of the electron heat flow parallel to the magnetic field ($\vec{q}_{e_\parallel}$) throughout the magnetized plasma volume, but especially in regions outside the reversal surface where good flux surfaces still exist.

The second method determines χ_{er} directly from the radial component of $\vec{q}_{e_\parallel}$ in the plasma fluid energy equation. In these calculations, two different models are employed for the $\vec{q}_{e_\parallel}$ closure and the resulting diffusivities are compared in various magnetic field configurations. One model addresses the anisotropy in $\vec{q}_{e_\parallel}$ verses $\vec{q}_{e_\perp}$ by writing $\vec{q}_{e_\parallel}$ as an enhanced diffusion process which depends on local gradients in the temperature, while the other model includes effects from non-local variations in the temperature by integrating along the magnetic fieldline[‡].

The high-order finite element version of the plasma fluid code NIMROD[§] was used in a simulation that results in a magnetic field characterized by large amounts of field line chaos and a reversal surface near the plasma edge. Subsequently, the energy equation only was evolved in this frozen magnetic field to make the diffusivity calculations.

*Research supported by the U.S DOE under grant no. DE-FG03-01ER54618.

[†] A. B. Rechester and M. N. Rosenbluth, Phys. Rev. Lett. **40**, 38 (1978).

[‡] E. D. Held, J. D. Callen, C. C. Hegna and C. R. Sovinec, Phys. Plasmas **8**, 1171 (2001).

[§] C. R. Sovinec, et al., UW CPTC Report 02-5 (2003)

Stability Study of the Hall-MHD Model

R. Torasso, E. Hameiri
Courant Institute of Mathematical Sciences, NYU

Because of a growing interest in plasmas with mass flow and its effects on various aspects of fusion studies such as turbulence, reconnection and equilibrium states, it becomes important to investigate the effects of two-fluid plasma model. We base our theory on Hall magnetohydrodynamics(HMHD), which encompasses single fluid ideal magnetohydrodynamics(MHD) with the addition of the Hall term. We have initiated a thorough study of linear stability of HMHD plasmas by analyzing, in particular, the effect that the Hall term bears on the stability of equilibria with no flow, which are also equilibrium states of classical MHD.

The linearized equations are cast in a Hamiltonian form, similar to the classical form for MHD plasmas with flow [1]. However, this requires the introduction of two displacement vectors, ξ_i and ξ_e. The Hamiltonian form enables easy comparison with MHD results. For example, subject to a mild additional restriction, such as incompressibility, we show that an MHD stable plasma is also HMHD stable. We develop general stability criteria as well as a bound on the complex eigenfrequencies of the system and their location in the complex plane. The bounds indicate that the phenomenon of overstability is the common case.

We examine with particular attention the theory of ballooning modes. From the ballooning expansion, we derive an equation that involves four displacement components, two each for ξ_i and ξ_e. We find that if ideal MHD is stable with regard to ballooning modes, then HMHD is also stable. We then concentrate on the special case of a cylindrical screw pinch. Stability involves five parameters, rather than just s and α, the shear and pressure gradient, respectively. This case is analytically tractable and leads to a fourth order algebraic equation for the eigenmodes. We determine that if ideal MHD is unstable with regard to ballooning modes, then HMHD is also unstable and the growth rate of the instability is actually increased by the Hall term. We are in the process of exploring the existence of a stability criterium for this special case. Also, for the general case we plan on studying the stability properties of HMHD ballooning modes by solving numerically the ballooning equations.

Work supported by USDOE grant No. DE-FG02-86ER53223

References

[1] E. Friedman and M.Rotenberg Rev. Mod. Phys. **32**, 898 (1960).

Symmetry Breaking Induced Plasma Viscosity and Resistive Wall Mode

K. C. Shaing
University of Wisconsin
Madison, WI 53706

Magnetohydrodynamic (MHD) activity, such as a magnetic island, or a resistive wall mode, breaks the toroidal symmetry in tokamaks. This leads to enhanced dissipation, especially in the toroidal direction, through the symmetry-breaking-induced plasma viscosity. We have developed an approach to investigate the symmetry-breaking effects on MHD activity in tokamaks. As illustrated in the theory for the magnetic island rotation frequency, we use the averaged plasma viscosity over the distorted magnetic surface to determine the bulk plasma flow, and use the local plasma viscous force (*i.e.* not surface averaged) to calculate the dispersion relation. Here, we apply the same approach for the resistive wall mode in tokamak plasmas. It is shown that the local viscous force is linear in the perturbed field in contrast to the surface-averaged viscosity, which is non-linear. We calculate a dispersion relation with the symmetry breaking induced viscosity as the main dissipation mechanism. General expression for the local viscous force that is useful for the low frequency resistive MHD activity will also be presented.

This work was supported by US Department of Energy under Grant No. DE-FG02-01ER54619 with the University of Wisconsin.

1C22

Generalised evolving background f_0 for plasma δf Particle-in-cell simulations

S.J.Allfrey, S.Brunner

Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, EPFL, 1015 Lausanne, Switzerland

The δf scheme aims to reduce the noise in the PIC method by *statistically* simulating only the evolution of a low variance function δf . The full distribution function is given by $f = f_0 + \delta f$, f_0 is referred to as the background. The importance of a good choice of the background has been demonstrated both theoretically [1][2] and practically [3]. However, it is clear that if f_0 is fixed and f evolves far from its initial value, δf is not going to remain a low variance function. Hence one seeks methods by which f_0 may be evolved in such a way as to keep the variance of δf small.

For collisional simulations Brunner *et.al.* [4] showed the practicality a scheme which evolved f_0 with fluid equations. When the system is not collision dominated such a fluid closure is not appropriate. However it is possible to maintain a representation of the background which is updated using statistical information from previous time steps.

We investigate the properties of such an evolving background scheme in the context of 2D Vlasov simulations.

[1] A. Y. Aydemir. A unified monte carlo interpretation of particle simulations and applications to non-neutral plasmas. *Phys. Plasmas*, 1:822, 1994.

[2] S. J. Allfrey and R. Hatzky. A revised delta-f algorithm for nonlinear pic simulation. *Comput. Phys. Commun.*, 154:98, 2003.

[3] R. Hatzky, T. M. Tran, A. Könies, R. Kleiber, and S. J. Allfrey. Energy conservation in a nonlinear gyrokinetic particle-in-cell code for ion-temperature-gradient-driven modes in θ-pinch geometry. *Phys. Plasmas*, 31:898, 2002.

[4] S. Brunner, E. Valeo, and J. A. Krommes. Collisional delta-f scheme with evolving background for transport times scale simulations. *Phys. Plasmas*, 6(12):4504, 1999.

1C23

Transport of Thermal Energy and its Relation to the Spontaneous Rotation Phenomenon*

V. Roytershteyn, B. Coppi
Massachusetts Institute of Technology, Cambridge, MA 02139

Abstract

An important process that is intrinsically connected to the transport of the plasma thermal energy is the "spontaneous toroidal rotation" of axisymmetric plasmas. This connection was pointed out first in the formulation of the so called accretion theory [1] and has been confirmed consistently by the most recent series of experiments [2] on this phenomenon. According to this theory, angular momentum in one direction is "accreted" on the material wall surrounding the plasma column [3] while angular momentum of the opposite direction (e.g. in the direction of the ion diamagnetic velocity in the case of the H-confinement regime) is carried from the edge toward the center of the plasma column by modes that are driven primarily by the plasma pressure gradient. We have verified that toroidal ballooning modes do not provide significant transport of net angular momentum. Thus toroidal "travelling modes", along the magnetic field, which instead can carry net angular momentum in the radial direction, have to be present and have significant amplitudes.

Two forms of the relevant quasilinear theory are derived identifying the ion pressure gradient as the driving factor for the angular momentum inflow and associating the sign of the ratio of the relevant poloidal to the toroidal mode numbers to that of the plasma toroidal velocity gradient. According to this analysis the source of the excitation of travelling modes is near the edge of the plasma column, from which the rotation velocity has been observed to enter, while the source of excitation of the ballooning modes is well within the plasma column where the ratio $\eta_i = d\ln T_i / d\ln n$ of the ion temperature gradient to the density gradient is maximum.

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

[1] B. Coppi, Nucl. Fusion, **41**, 1 (2002).
[2] E. S. Marmar, et al., Fusion Energy 2002 (IAEA, Vienna) Paper OV/4-1
[3] B. Coppi, et. al., Fusion Energy 1998 (IAEA, Vienna) Paper IAEA-F1-CN-69-Th3/7.

1C24

δf Simulation of collisionless and semi-collisional Tearing Modes

W. Wan, Y. Chen and S. E. Parker
University of Colorado, Boulder, CO 80309

The evolution of the collisionless tearing mode is studied using a three-dimensional particle-in-cell simulation model that uses the δf-method with the split-weight scheme to enhance the time step, and a novel algorithm to accurately solve the Ampere's equation for experimentally relevant β values, $\beta \frac{m_i}{m_e} \gg 1$.[1] We use the model of drift-kinetic electrons and gyrokinetic ions. Linear simulation results are benchmarked with eigenmode analysis for the case of fixed ions, as can be shown that in small box simulations the ions response can be neglected. The nonlinear dynamics of magnetic islands will be studied and the results will be compared with previous theoretical studies.[2]

Recently we add collision operator to the particle weight equation to study tearing mode in the Rutherford regime. Width of the perturbed current, growth rate and saturation level are studied from linear and nonlinear simulation and compared with theory.

[1] Y. Chen and S.E. Parker, J. Comput. Phys. **198**, 463 (2003)
[2] J.F. Drake and Y. C. Lee, Phys. Rev. Lett. **39**, 453 (1977)

Transport and bootstrap current in a small aspect ratio torus

R. B. White, D. A. Gates
Plasma Physics Laboratory, Princeton University, P.O.Box 451, Princeton, New Jersey 08543

Synopsis

Transport theory at high aspect ratio is based on the "small gyro-radius expansion", which assumes that $\rho_i/a \equiv \rho* << 1$. In addition, it is generally assumed that $|B_\theta/B_\phi| << 1$. In low aspect ratio tokamaks [1], often referred to as spherical torii. these assumptions are invalid. They are also fundamental to the derivation of the drift kinetic equation.

In order to determine the magnitude of the correction to collisional transport and bootstrap current due to finite gyro-radius, we compare the result of the gyro-average orbit code ORBIT [2, 3] with those from the full orbit code GYROXY[4]. We coin the word omniclassical to refer to transport calculations based on full particle orbits in general toroidal geometry with arbitrary aspect ratio.

Two equilibria from the National Spherical Torus Experiment (NSTX)[5], were chosen as representative low aspect ratio equilibria. In NSTX for most particle orbits the displacement of the particle from its nominal flux surface is much larger than the neoclassical banana width. To carry out the numerical simulations, monoenergetic distributions of particles are allowed to evolve under the influence of pitch angle scattering.

The resultant omni- to neoclassical bootstrap and diffusivity ratios are determined versus outboard radius for a large beta equilibrium. Both bootstrap current and diffusion are significantly larger than neoclassical, also in a low beta discharge.

*This work was supported by the U.S. Department of Energy Grant under contract number DE-AC02-76CH03073.

References

[1] Y-K. M. Peng and D. J. Strickler, Nucl. Fusion **26**, 769 (1986)

[2] R. B. White and M. S. Chance Phys. Fluids **27**, 2455 (1984)

[3] R. B. White, Phys. Fluids B **2**, 845 (1990)

[4] R. B. White, L. Chen, Z. Lin, Phys. Plasmas **9** 1890 (2002)

[5] M. Ono, S. M. Kaye, Y. -K. M. Peng, *et al.*, Nucl. Fusion **40**, 557 (2000)

1C26

Radial spreading of electron temperature gradient driven turbulence

Ö. D. Gürcan and P. H. Diamond

Department of Physics, University of California,

*San Diego, La Jolla CA 92093-0319, USA**

Abstract

Particle and heat transport for the ion and electron temperature gradient driven modes have certain properties which can not be explained from simple linear analysis. One such important phenomenon is the existence of turbulence in regions where the local linear growth rate vanishes. One attempt at explaining this is the idea of turbulence propagation, or spreading. Driven in regions for which $\gamma > 0$, turbulence may in fact propagate into regions for which $\gamma = 0$. In this work we use reductive perturbation methods, to derive one such model for the intensity of ETG turbulence. The derived model has all the physically expected terms, hence it fits into the framework of previous scaling analysis but puts this on a firm theoretical foundation. In addition, the model takes into account spreading of turbulence due to linear dispersion, which may be effective, especially during the initial phase before nonlinear saturation.

*Electronic address: ogurcan@physics.ucsd.edu

1C27

Fluid description of ion dynamics in a toroidally confined plasma

Abinadab Dieter and R. D. Hazeltine

Institute for Fusion Studies, The University of Texas at Austin

Abstract

Fluid equations describing ion dynamics in a toroidally confined plasma at low collision frequency are derived. The ions are assumed to be magnetized in the sense that relevant scale lengths are much longer than the ion gyroradius, and time scales of interest are assumed long compared to the ion bounce time. These assumptions are consistent with, for example, the evolution of unstable magnetic islands, as well as conventional transport. A special case of the present description is the quasistatic, axisymmetric state with nearly uniform pressure and density on flux surfaces. In that case the equations reproduce the radial ion heat transport predicted by neoclassical transport theory. The essential feature of our derivation is its emphasis on heat flow in the direction of the magnetic field.

Effects of Flux Surface Shape on Turbulent Transport and A Modification of the Split-weight Scheme

Y. Chen and S. E. Parker

Univ. of Colorado, Boulder, Colorado, USA

Abstract. GEM[1] is a gyrokinetic simulation code for studying drift-wave turbulence and kinetic tearing modes. It is an explicit δf particle code that has fully kinetic electron dynamics and magnetic field perturbations. In this presentation the implementation of general equilibrium, in particular the Miller equilibrium model [2], using the field-line-following coordinates will be described. Equilibrium quantities such as the Jacobian, poloidal field strength, etc., are computed and stored as numerical tables during initialization, and are evaluated at the particle locations through interpolation. Effects of flux surface shape on drift-wave turbulence will be studied, in parallel to a previous study using gyro-fluid simulations [3]. It is observed that elongation can have a strong stabilizing effect, and significantly shift the Dimits' Shift region toward larger R/L_T.

We will also describe a modification of the split-weight scheme [4], in which the adiabatic electron term $n_0 \frac{e\phi}{T_e}$ in the quasineutrality condition is computed using the numerically evolved marker distribution, similar to the $\frac{\omega_{pe}^2}{c^2} A_{\|}$ term in the Ampere's equation [Ref. 1]. This modification has little effects on the most unstable modes, but can have small effect on the long wavelength zonal flow modes and consequently can change the turbulent flux if the saturated turbulence is dominated by such flows.

[1]Y. Chen and S. E. Parker, Journal of Computational Physics 189 (2003) 463

[2]R. L.Miller, M. S. Chu, J. M. Greene, Y. R. Lin-Liu and R. E. Waltz, Physics of Plasmas 5 (1998) 973

[3]R. E. Waltz and R. L. Miller, Physics of Plasmas 6 (1999) 4265

[4]I. Manuilskiy and W. W. Lee, Physics of Plasmas 7 (2000) 1381

Control of resistive wall modes – comparison of normal and tangential B sensing

Christopher Jones[1], John M. Finn[1] and Luis Chacon[1]

[1] Los Alamos National Laboratory

Abstract

We study control of linear and nonlinear resistive wall modes (RWM) with a slab (or cylindrical) model with complex gain $G_r + iG_i$, i.e. proportional gain with a possible phase shift. G_i is equivalent to a closer-fitting wall and G_i is equivalent to rotation. When the measured field is the *normal* component of magnetic field at the wall, the real gain required to give benign saturation of the RWMs can be *much* less than that required for linear stabilization, particularly near the threshold for instability with a perfectly conducting wall (the ideal wall β). Moderate real gain can reduce the amplitude of the nonlinear (wall locked) state to a benign level. We formulate the resistive wall - feedback coil boundary conditions in cylindrical geometry in terms of components of the inverse of the inductance matrix, and show the formalism for sensing based on (i) normal (radial) component of the magnetic field $\mathbf{B}$ inside (or outside) the resistive wall, (ii) tangential component of $\mathbf{B}$ inside the wall, and (iii) tangential component of $\mathbf{B}$ outside the wall. We compare the relation between these schemes and the efficacy of feedback based on the three. We will also show results on fitting equilibrium parameters with experimental measurements of the field by means of a Grad-Shafranov solver, taking into account a realistic estimate of the covariance matrix of the field measurements, related to the noise due to fluctuations such as ELMs.

1. J. M. Finn and L. Chacon, "Control of Linear and Nonlinear Resistive Wall Modes", to appear in *Phys. Plasmas* (2004).

1C30

Electron Thermal Transport in Tokamak: ETG or TEM Turbulences?

Y. Li* and Z. Lin

University of California, Irvine, CA, USA

The renewed interest in electron temperature gradient (ETG) modes comes from numerical simulations of the ETG turbulence using the flux-tube geometry. These simulations find that radially elongated turbulence eddies, or streamers, can drive a transport level much higher than the mixing length estimates. However, the radial scale length of the ETG streamers is comparable to the radial box size of the flux-tube simulation. This contradicts the fundamental assumption of the flux-tube simulation, which uses a radially periodic boundary condition assuming that the radial correlation length of the turbulence eddies is much shorter than the radial box size.

In our studies, a massively parallel, global gyrokinetic toroidal code[1] (GTC) has been utilized to simulate electrostatic ETG turbulences. We use the "cyclone" parameters of a representative DIII-D H-mode plasma. The size of the tokamak is roughly that of the DIII-D with the minor radius $a=8000\rho_e$. The simulation geometry is an annulus of $r/a=[0.4,0.6]$ with a fixed radial boundary condition and with the whole flux-surface. Other simulation parameters[2] are similar to that in the flux-tube simulation. We find that the electron thermal conductivity is only about three times of that predicted by the mixing length rule, even though the radial scale length of ETG streamers is comparable to our simulation radial box size of up to $1600\rho_e$. The transport level is well bellow experimental values and is about an order of magnitude smaller than that reported by flux-tube simulations. We perform a machine size scan and find that the transport scaling is gyro-Bohm for $a>2000\rho_e$ although the radial length of ETG streamers scales with the machine size. Our GTC results are closer to those from a global fluid simulation[3] of ETG modes with a small tokamak size of $a=100\rho_e$, and from a fluid simulation[4] in the slab geometry. We further find that the ETG transport level is much smaller than that driven by the trapped electron mode (TEM) turbulence for the same plasma parameters. This work is supported by U.S. DOE Cooperative Agreement No. DE-FC02-03ER54695 at UC Irvine, and in part by the DOE SciDAC plasma microturbulence project.

References

[1] Z. Lin *et al*, *Sciences* **281**, 1835 (1998).
[2] Z. Lin and T. S. Hahm, *Phys. Plasmas* **11**, March (2004).
[3] B. Labit and M. Ottaviani, *Phys. Plasmas* **10**, 126 (2003).
[4] J. Li and Y. Kishimoto, *Phys. Plasmas* **9**, 1241 (2002).

* Permanent address: University of Science and Technology of China, Hefei, China

The Effects of Energetic Ions on Magnetic Islands in Toroidal Plasmas

X.Liu, C.C.Hegna
Dept. of Engineering Physics, University of Wisconsin
Madison, WI 53706

A kinetic theory for the interaction of an energetic ion population with an isolated magnetic island in a tokamak plasma is presented. In this work, we examine islands whose characteristic widths are larger than the energetic ion gyro radius but smaller than the energetic ion banana width. In this regime, the energetic ion response to the island has a non-local feature. When solving the drift kinetic equation for the energetic ions, a change in radial coordinate to the drift orbit is used to account for this behavior. After bounce averaging a kinetic equation for the ions, a lowest order distribution function is found. By considering the quasineutrality relation, the parallel current ($J_{//}$) in response to the energetic ions is calculated. Using this current in the "dispersion relation", the island width evolution equation is determined. A pair of self-consistent equations for the islands' width, w, and its propagation frequency, ω, is to be derived. The results are to be compared with those for large island width so as to yield a description of magnetic island width evolution from sub-banana width to macroscopic scale lengths.

*Research supported by US DoE under grant No. DE-FG02-86ER53218.

1C32

Electromagnetic gyro-kinetic simulation with a fluid-kinetic hybrid electron model

Y. Nishimura[1], Z. Lin[1], L.Chen[1], J. Lewandowski[2], S. Ethier[2], and W. Wang[2]
[1]Physics and Astronomy, University of California, Irvine CA, 92697-4575
[2]Princeton Plasma Physics Laboratory, Princeton NJ, 08543

In gyrokinetic simulations, overcoming steep numerical constraints imposed by the kinetic electrons has been a crucial issue. The split-weight scheme[1] separates the adiabatic and the non-adiabatic electron responses which reduced the statistical noise of the particle simulation. Lin and Chen furthered a hybrid electron model[2] which can relax the numerical constraints. Based on a small parameter expansion by the square-root of the electron-ion mass ratio, the hybrid model solves the adiabatic response in the lowest order and solves the kinetic response in the higher orders. The model preserves the linear and the nonlinear wave-particle interactions. One of the advantages of the hybrid model appears in the simplified field equation. A new finite element field solver is implemented in the GTC code[3] for the electrons with an assistance of algebraic multi grid method.

We initially focus on the effects of the non-tearing-parity modes on the transport using the hybrid model. Electromagnetic fluctuations can enhance drift wave induced turbulent transport even when the magnetic topology is preserved. In the presence of magnetic flutter effects, one expects the guiding center drifts associated with the magnetic perturbation to be comparable to the electrostatic $E \times B$ drifts. Furthermore, trapped electrons having their own adiabatic invariant can cause the temperature to vary along the magnetic field lines, and thus contribute to net radial transport (rapidly bouncing trapped particles are insensitive to the low frequency magnetic perturbations). At a critical β value, we expect excitations of new branches of electromagnetic modes, that are the Alfvenic ion temperature gradient mode (AITG)[4] and the kinetic ballooning mode (KBM). The linear growth rate and the onset (the threshold β value) of the modes are investigated. This work is supported by Department of Energy (DOE) Cooperative Agreement No. DE-FC02-03ER54695 (UCI), DOE Contract No. DE-AC02-76CH03073 (PPPL).

References

[1] I. Manuilskiy and W. W. Lee, Phys. Plasmas **7**, 1381 (2000); J. L. V. Lewandowski, Phys. Plasmas **10**, 3204 (2003).
[2] Z. Lin and L. Chen, Phys. Plasmas **8**, 1447 (2001).
[3] Z. Lin, T. S. Hahm, W. W. Lee, et al., Phys. Plasmas **7**, 1857 (2000).
[4] G. Zhao and L. Chen, Phys. Plasmas **9**, 861 (2002).

1C33

Simulation of Pellet Injection in Tokamaks using 3D Adaptive Mesh Refinement

R. Samtaney[1], S. Jardin[1]

[1] Princeton Plasma Physics Laboratory
Princeton University, Princeton, NJ 08543

Abstract

We present results of Adaptive Mesh Refinement (AMR) simulations of the pellet injection process, a proven method of refueling tokamaks. AMR is a computationally efficient way to provide the resolution required to simulate realistic pellet sizes relative to device dimensions. The mathematical model comprises of single-fluid resistive MHD equations with source terms in the continuity equation along with a pellet ablation rate model. The numerical method developed is an explicit unsplit upwinding treatment of the 8-wave formulation, coupled with a MAC projection method to enforce the solenoidal property of the magnetic field. The Chombo framework is used for AMR. While the dominant mass redistribution occurs along the field lines, this is accompanied by "anomalous" transport which displaces the pellet mass in the outward radial direction[1]. The role of the $E \times B$ drift in mass redistribution during high field side (HFS) and low field side (LFS) pellet launches in tokamaks is examined. Fig. 1 clearly shows the asymmetry in density distributions poloidal slices at the mean toroidal pellet location for both the HFS and LFS cases.

This work was supported by USDOE Contract no. DE-AC020-76-CH03073. This research used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

[1] R. Samtaney, S. C. Jardin, P. Colella, D. F. Martin, "3D Adaptive Mesh Refinement Simulations of Pellet Injection in Tokamaks", to appear in Computer Physics Communications, 2004.

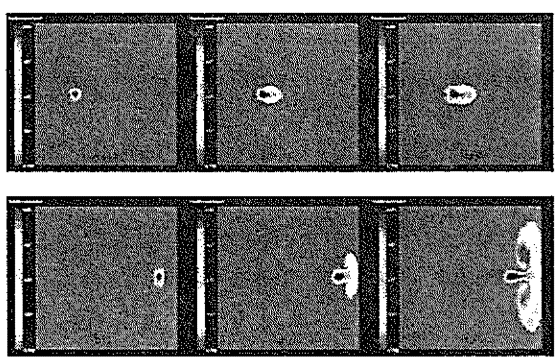


Figure 1: Density field in a poloidal cross-section. (a1) HFS $t = 2$, (a2) HFS $t = 20$, (a3) HFS $t = 60$, (b1) LFS $t = 2$, and (b2) LFS $t = 20$, and (b3) LFS $t = 60$.

1C34

Stability of pure electron plasmas on magnetic surfaces

Allen H. Boozer

Department of Applied Physics and Applied Mathematics
Columbia University, New York, NY 10027

Abstract

The stability of pure electron plasmas is developed for perturbations that are of sufficiently low frequency to preserve force balance and the equality of the electron temperature along the magnetic field lines. These two constraints are shown to imply an otherwise ideal plasma is stable to all perturbations of the electric potential. The source of this robust stability is that these two constraints eliminate plasma flows that cross the magnetic surfaces. Since the magnetic surfaces are rigid, the elimination of plasma flows across the surfaces means the plasma cannot effectively tap the enormous free energy that exists in the repulsive electrostatic potential.

Toroidal plasmas with magnetic surfaces have been used for about half a century to confine quasi-neutral plasmas. Proposals have only recently been made to confine non-neutral plasmas in toroidal systems with magnetic surfaces using either an axisymmetric levitated ring or a stellarator geometry. A stellarator for confining non-neutral plasmas, the Columbia Non-Neutral Torus (CNT), is being built by Prof. Thomas Pedersen. The theory of pure electron plasmas confined on magnetic surfaces differs significantly from that of quasi-neutral plasmas. In pure electron plasmas, the plasma density is sufficiently low that its current has a negligible effect on the magnetic field. Force balance and rapid heat transport along the magnetic field lines determine the form of the electron density, but otherwise force balance in a non-neutral plasma is simple. The primary equilibrium equation is the equation for the electric potential, which is given by Poisson's equation. The ratio of the change in the potential to T/e is approximately the square of plasma radius divided by the Debye length. The CNT stellarator will be used to study not only pure electron plasmas, but also partial neutralized and quasi-neutral plasmas

The author would like to thank Thomas Sunn Pedersen for many useful discussions. This work was supported by the NSF/DoE partnership in plasma science grant Phy-03-17359.

Alfvén Eigenmode stability with beams in ITER-like plasma

N. N. Gorelenkov[†], H. L. Berk[‡], R. V. Budny[†]

[†] *Princeton Plasma Physics Laboratory*
P.O. Box 451, Princeton, NJ 08543-0451.
[‡] *IFS, Austin, Texas.*

ABSTRACT

The toroidicity-induced Alfvén Eigenmodes (TAE) in a proposed ITER burning plasma experiment, driven unstable by two groups of energetic particles, α-particle fusion products and tangentially injected beam ions are studied. Both species are super-Alfvénic but have different pitch angle distributions and the drive for the same pressure gradients is typically stronger from co-injected beam ions as compared to the isotropically distributed α-particles. The study emphasizes the role of the anisotropy in the beam ion distribution function on TAE growth rate via the additional velocity space drive. At the injection energy $E_{b0} = 1MeV$ TAEs are predicted to be stabilized in the nominal ITER discharges if the injection angle is perpendicular to the magnetic axis. TAEs are marginally unstable if the injection aims at the plasma center where the ion Landau damping is strong, whereas with the off-axis NBI the instability is stronger with the growth rate above 1% of TAE mode frequency.

The effect of TAEs on fast ion beta profiles is evaluated on the bases of a quasi-linear diffusion model which makes use of expressions for the local growth and damping rates and calculates the relaxed alpha particle profiles by imposing power balance between the alpha particle fusion power production of the background plasma with the power transferred from alpha particles to electrons due to drag. These results illustrate the parameter window that is available for plasma burn when TAE modes are excited.

Studies of plasma shaping effects on ITG/TEM turbulence with the GS2 gyrokinetic code and a local linear gyrokinetic code*

E. A. Belli[1], G. W. Hammett[1], W. Dorland[2], R. V. Budny[1]
[1]*Princeton Plasma Physics Laboratory*
[2]*Univ. of Maryland*

The effects of flux surface shape and other plasma parameters on the gyrokinetic stability and transport of tokamak plasmas are being studied. A local linear gyrokinetic code has been developed to aid in these studies. It includes models of the effects of plasma shaping, magnetic shear, and toroidal geometry by using representative values of $k_{\|}$, $k_{\perp}^2$, ω_d, etc. averaged over a trial eigenfunction, using the same geometrical information available in the full GS2 gyrokinetic code. Thus it can use either a full numerical equilibrium or a local parameterized equilibrium such as developed by Miller et.al †. The resulting reduced model is able to follow the scaling of the linear growth rate from the full GS2 code in the collisionless, electrostatic limit, with single and multiple gyrokinetic ion and electron species, for a range of shaped flux surface equilibria. A simple model of trapped particle effects also works fairly well. Extensions to include magnetic fluctuations and accurately recover the ideal ballooning limit were found to be more difficult, requiring coupling to higher order Hermite basis functions. The most stabilizing influences on the linear growth rate are seen with 1) high elongation and elongation gradient with high triangularity at a fixed α, and 2) high triangularity at high α at a finite elongation. Using GS2, we have also recently extended these results to include comparisons with JET data and to study the scaling of nonlinear turbulence levels with shaping parameters.

---

*Supported by DoE Contract No. DE-AC02-76CH03073

†R. Miller, M.S. Chu, J.M. Greene et al, Phys. Plasmas **5**, 973 (1998).

Kinetic Damping of Toroidal Alfvén Eigenmode Revisited*

G.Y. Fu
Princeton Plasma Physics Laboratory, Princeton, NJ

H.L. Berk
Institute for Fusion Studies, Austion, TX

The problem of kinetic damping of Toroidal Alfvén Eigenmode is revisited. This is motivated in part by recent experimental test of damping models for TAE in JET where the "radiative damping" was found to be negligible and the calculated damping (mainly the electron collisional damping) is much smaller than the measured value[1]. On the other hand, numerical results of the global gyrokinetic code PENN indicated that mode conversion can occur near the center of plasma which resulted in damping rates comparable to the JET measurement[2]. In order to resolve this discrepancy, we re-consider this problem by using a simpler model including the key MHD physics of TAE and the kinetic Alfvén waves with an electron damping model included to weakly damp the kinetic Alfvén excitations so that the mode couping appears as a damping . For a cylindrical model, we show analytically and numerically that there is no mode coupling (or mode conversion) between the global MHD modes and the kinetic Alfvén waves when suitable boundary conditions at the edge are chosen to prevent kinetic Alfvén wave generation there. We extended the numerical model to a simplified toroidal problem and no resolvable mode conversion to kinetic Alfvén waves has been found for a range of q profiles, in contrast to the finding in Ref. [2]. On the other hand we have identified absorption processes due to the Alfvén continuum that should be relevant to the damping mechanisms that are relevant to the JET experiments which have normally not been taken into account in many numerical codes. Details of numerical results for experimental parameters and profiles will be presented.

References

[1] D. Testa, G.Y. Fu, A. Jaun et al., Nucl. Fusion 43, 479 (2003).
[2] A. Jaun, A. Fasoli, and W.W. Heidbrink, Physics of Plasmas, 5, 2952(1998)

*Supported by DOE DE-AC02-76-CHO-3073.

1C38

High confinement modes with radial structure

B.A. Carreras, D. del-Castillo-Negrete, and V.E. Lynch

Fusion Energy Division
Oak Ridge National Laboratory
Oak Ridge, TN, 37831-6169

Since the discovery of the L to H transition, several theoretical models have been proposed. These models involve various mechanisms for the creation of transport barriers including ion orbit losses, critical gradients, Reynolds stress, magnetic shear, and atomic physics. Due to the lack of sufficiently high spatial and temporal resolution, it is difficult to have a clear experimental test to select the dominant mechanisms responsible for the transition. However, recent C-mod experimental results using ECE temperature measurements offer the possibility of improved diagnostics with increased radial resolution during and after the transition [1]. Motivated by this, in this presentation we investigate the radial structure of high confinement modes in the context of phase transition models. In a previous publication [2] we discussed the spontaneous formation of shear flows with nontrivial radial structure in a flow-fluctuation model. By spontaneous we mean that, in this model the radial structures arise as nonlinearly saturated finite-k instabilities, and not as a result of externally imposed inhomogeneities. Here we incorporate to the two-fields model a transport equation for the pressure with the corresponding coupling to the fluctuations via a pressure gradient drive [3]. Of particular interest is the study of pedestal formation resulting from the plasma self-organization driven by the self-consistent interaction of fluctuations, shear and pressure gradients. The model describes the plasma edge with an energy flux coming from the core, which is used as a boundary condition for the pressure transport equation. As the energy flux increases, there is an L-H transition bifurcation which is described near marginal instability using a reduced Ginzburg-Landau model for the shear flow coupled to a transport equation for the pressure. For higher values of the energy flux, a second transition takes place in which the H mode exhibits a finite-k instability. Numerical results show that this instability leads in the nonlinear regime to the spontaneous formation of a pedestal in the pressure profile, where the effective diffusivity exhibits a sharp drop. A further increase of the energy flux leads to multiple pedestals across the simulation domain.

[1] Hubbard A.E, B.A. Carreras, N.P. Basse, D. del-Castillo-Negrete, et. al.,accepted for publication in Plasma Phys. Control. Fusion (2004).
[2] del-Castillo-Negrete D., and B.A. Carreras, Phys. Plasmas. **9**, 118, (2002).
[3] del-Castillo-Negrete D., B.A. Carreras, and V.E. Lynch, submitted to Plasma Phys. Control. Fusion (2004).

1C39

Hybrid multi-wave model for relativistic wave–plasma interaction

E. G. Evstatiev, W. Horton, P. J. Morrison
Department of Physics and Institute for Fusion Studies, University of Texas at Austin
Austin, TX 78712

Abstract

A hybrid fluid-particle model is presented for relativistic beam–plasma interaction. The derivation uses a Lagrangian of the system of multiple waves and particles, and a slowly varying amplitude approximation to obtain a finite-dimensional system of ordinary differential equations for the wave amplitudes and the particle coordinates and momenta. The system is three-dimensional and relativistic. The model allows for studying of electron acceleration in a plasma channel. It is shown that the linear growth rate of the plasma wave can be enhanced when electromagnetic waves are present. Conditions for more efficient energy exchange between electrons and waves, and between plasma and electromagnetic waves are determined.

1C40

Distinguishing Characteristics of SOC-like Systems

Ryan Woodard[1] David Newman[1] Raul Sanchez[2] and B. A. Carreras[3]

[1]Department of Physics and Geophysical Institute, University of Alaska, Fairbanks, Alaska

[2]Department of Physics, Univ. Carlos III, Madrid, Spain

[3]Oak Ridge National Laboratory, Oak Ridge, TN

Abstract.

As Self-Organized Criticality (SOC) has been suggested as a relevant model for more and more plasmas, from magnetically confined fusion plasmas to space plasmas and other geophysical systems, the questions of how do we distinguish SOC systems and what do we gain by using this paradigm becomes more important. In this poster we will describe some of the dynamic signatures that may be used to compare systems. These include power spectra (in which people look for the ubiquitous 1/f signature, which might not be needed), quiet time statistics and Hurst exponent analysis. This discussion will include both the strengths and limitations of these measures and the types of regimes one must observe to further clarify the dynamics of the system. An explanation for the appearance or lack of the 1/f regime in the power spectrum will be given and we will also discuss analysis limitations due to data length effects. Finally, some comments will be made on the practical usefulness of SOC and extensions of this paradigm.

1C41

Modeling of magnetic perturbations and energy confinement in SSPX spheromak

M.V. Umansky, R.H. Bulmer, D.N. Hill, L. LoDestro, H. McLean,
W.M. Nevins, D.D. Ryutov, and S. Woodruf

Lawrence Livermore National Laboratory
Livermore, CA 94551

Abstract

The effects of magnetic field fluctuations on the quality of confinement in SSPX spheromak [1] plasmas are studied by analyzing a perturbed magnetic field. The unperturbed axisymmetric magnetic field is calculated from MHD equilibrium. We explore physically motivated models for non-axisymmetric perturbation such as the external perturbation coil experiment [2] and the central column instability [3]. We calculate the spatial spectrum of the perturbation that determines its effect on the magnetic topology and use numerical line integration to construct Poincare maps. For realistic magnitude of the perturbation the calculations show formation of islands on main resonant surfaces and appearance of stochastic regions in the outer part of the plasma, which is consistent with experimental T_e measurements [4]. The effective heat transport induced by the presence of stochastic magnetic field is calculated by a Monte-Carlo procedure, and the results are compared with the experimental data.

[1] E. B. Hooper et al., Nucl. Fusion **39**, 863 (1999).
[2] H. S. McLean et al., Bull. Am. Phys. Soc. **48**, 150 (2003).
[3] D. D. Ryutov et al., Bull. Am. Phys. Soc. **48**, 167 (2003).
[4] S. Woodruff et al., Bull. Am. Phys. Soc. **48**, 150 (2003).

Work performed for U.S. DOE by UC LLNL under contract W-7405-Eng-48.

1C42

Bifurcation analysis of the Dimits shift: Conceptual issues and resolutions*

R. A. Kolesnikov and J. A. Krommes
Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08543

Abstract

It is well established that the Dimits upshift[1] is due to the suppression of drift-wave fluctuations by zonal flows.[2] However, systematic calculation of the width of the nonlinearly stable regime as a function of control parameter (background temperature gradient) presents some conceptual challenges. To illustrate the difficulties, a simple fluid model of ion-temperature-gradient-driven turbulence[3] is studied with the aid of systematic bifurcation analysis. The presence of very weakly damped zonal modes in the eigenspectrum is a complicating feature that precludes simple application of cookbook formulas for local bifurcations and construction of the center manifold. An alternate procedure is described and used to obtain a model system of coupled amplitudes for drift waves, zonal flows, and sidebands. The presence of a stable fixed point for finite distance above linear threshold is identified with the Dimits-shift regime. Further complications include the necessity for multiple-scale analysis to deal with a near-continuum of modes that become unstable nearly simultaneously. The method is related to the reductive-perturbation approach employed by Weiland and coworkers,[4,5] but differs fundamentally in its treatment of the sidebands.

* Work supported by U. S. Dept. of Energy Contract No. DE-AC02-76-CHO-3073.

1 A. M. Dimits, G. Bateman, M. A. Beer *et al.*, Phys. Plasmas **7**, 969 (2000).
2 B. N. Rogers, W. Dorland, and M. Ketschenreuther, Phys. Rev. Lett. **85**, 5336 (2000).
3 M. A. Beer, Ph.D. thesis, Princeton University, 1995.
4 S. Dastgeer, S. Mahajan, and J. Weiland, Phys. Plasmas **9**, 4911 (2000).
5 J. Weiland, S. Dastgeer, R. Moestam, I. Holod, and S. Gupta, Excitation of zonal flows and fluid closure, J. Plasma Fusion Research (2004) (in press).

Theory of Rapid Transport by 3D Blobs*

D. A. D'Ippolito, J. R. Myra and D. A. Russell

Lodestar Research Corporation, Boulder, CO 80301

There has been a great deal of recent work on the theory of SOL transport by coherent density structures called "blobs" [1,2]. This work is motivated by experimental observations of high-density structures aligned parallel to the magnetic field but very localized perpendicular to the field. Diagnostics on tokamaks and on linear experiments show that these structures move radially outwards contributing to the intermittent transport measured in the SOL. A recent review [3] of 2D blob theory and its experimental motivation shows that the simple theory provides a robust mechanism for radial transport in the presence of an outward force (curvature, centrifugal, or neutral wind) and has several points of qualitative agreement with experiments and turbulence simulations. The 2D theory assumes no variation along the field lines and good connection of the blobs to the sheaths, so that the blob charge polarization is limited by parallel current flow into the sheaths. Subsequently, 3D turbulence simulations with neutral sources were carried out for DIII-D plasmas near the density limit [4], and preliminary analysis [5] of the simulation results showed that blobs were produced by the turbulence with some of the features expected from the simple 2D theory. Further analysis [6] of the 3D high-density simulation showed that in fact the radial blob velocity exceeds that predicted by the 2D sheath-connected blob model, and the temperature has a dipole structure, neither of which can be explained by the earlier theory. Moreover, this simulation is in the regime where the turbulence and the coherent structures acquire a ballooning structure along the field lines making the physics essentially three dimensional. In a separate study, it has been shown that the degree to which the blob is electrically connected to the sheath influences its rotation and many aspects of its dynamics [7].

These results point to the need for a 3D theory of blob transport which takes into account the details of parallel connection along the field line, especially of the currents induced by the blob. Here, a first attempt at such a theory will be discussed. It is shown that a combination of the curvature and thermoelectric terms in Braginskii theory permit a 3D blob solution in which the parallel currents are converted to perpendicular currents near an X-point [8] in such a way as to support a temperature dipole (along with the usual dipole charge and vorticity) in the blob. The induced potential and resulting outwards E×B drift are much larger for the 3D solution than for 2D model. Both of these features agree qualitatively with the 3D simulations [6]. The scaling of three mechanisms for perpendicular current generation (collisional electron conductivity, ion viscosity, and ion polarization current) will be compared and the dominant one in the simulation [4] will be identified. Finally, the scaling of the 3D blob velocity with plasma parameters will also be examined to see if this mechanism could play a role in the density limit.

* Work supported by US DOE grant DE-FG02-97ER54392.

[1] S. I. Krasheninnikov, Phys. Lett. A **283**, 368 (2001).
[2] D. A. D'Ippolito, J. R. Myra, and S. I. Krasheninnikov, Phys. Plasmas **9**, 222 (2002).
[3] D. A. D'Ippolito et al., 2003 PET meeting; to be published in Contrib. Plasma Phys. **44** (2004).
[4] X. Q. Xu et al., Bull. Am. Phys. Soc. **48**, 184 (2003), paper KP1 20.
[5] D. A. Russell et al., Bull. Am. Phys. Soc. **48**, 184 (2003), paper LP1 71.
[6] D. A. Russell et al., this conference.
[7] J. R. Myra et al., this conference.
[8] S. Krasheninnikov, D. Ryutov, and G. Yu, 13th Toki Conf, to be published in J. Plasma Fus. Res. (2004).

Convective transport in the scrape-off-layer by non-thermalized spinning blobs *

J. R. Myra, D. A. D'Ippolito and D. A. Russell
Lodestar Research Corporation, Boulder, CO 80301

S. I. Krasheninnikov, and G. Q. Yu,
University of California at San Diego, La Jolla, CA 92093

A blob, or blob filament, is a localized region of enhanced density (and possibly temperature) which convects coherently in the scrape-off-layer (SOL).[1] Blobs, which typically have spatial scales ~ 1 cm perpendicular to B and are highly elongated along B, are especially important for describing SOL transport. Here, 2D models of blob propagation in the SOL are generalized to include the internal temperature profile of the blob, $\nabla_\perp T_e$. For blobs that are connected in the parallel direction to sheaths, this generalization provides a mechanism for blob internal spin and enables consideration of SOL energy transport. Solutions with aligned density and temperature contours satisfying the "hot blob" equations are considered. It is shown that spin increases blob coherence, prevents the formation of extended radial streamers or fingers, reduces the radial convection velocity by mixing of the curvature-induced charge polarization, and provides a new mechanism for poloidal motion of the blob. Additionally, spinning blobs are shown to survive as coherent objects in the presence of weak externally sheared flows, and have blob speeds that depend on the sign of the spin relative to the external sheared flow. Hot blobs are subject to (secondary) instability drives that do not impact thermalized blobs: (i) rotational instability that can cause the blob to shed its outer layers[2] and (ii) the $\nabla_\perp T_e$ sheath term.[3] Because of the sensitivity of blob transport to spin, the results provide motivation for investigating the physics of parallel disconnected blobs,[4,5] and the relationship of spin and disconnection physics to ELM propagation and the density limit.

* Work supported by USDOE grant DE-FG02-97ER54392.

1. S.I. Krasheninnikov, Phys. Lett. A **283**, 368 (2001); D.A. D'Ippolito et al., Phys. Plasmas **9**, 222 (2002).
2. D. A. D' Ippolito, et al. PET Meeting, to be published in Contr. Plasma Phys**44** (2004).
3. H.L. Berk, R.H. Cohen, D.D. Ryutov, et al., Nucl. Fusion **33**, 263 (1993).
4. D. A. Russell, et al. this conference.
5. D. A. D'Ippolito, et al. this conference.

1C45

On the Structure of Blobs in Turbulent BOUT Simulations*

D. A. Russell, D. A. D'Ippolito and J. R. Myra

Lodestar Research Corporation, Boulder CO 80301

W. M. Nevins and X. Q. Xu

Lawrence Livermore National Laboratory, Livermore CA 94551

Diagnostics on tokamak experiments[1] and 3D turbulence simulations[2,3] suggest that particle and perhaps energy transport in the scrape-off-layer (SOL) are dominated by filaments of enhanced density called *blobs*.[4,5] Understanding blob dynamics is an important goal in the context of edge and SOL confinement. Although blobs are born intermittently under conditions of strong turbulence near the separatrix, radial blob motion across the SOL is simple (ballistic) and may be amenable to reduced modeling that will, it is hoped, shed light on possible methods of controlling edge transport and improving confinement.

We explore the anatomy of blobs gleaned from a series of BOUT DIII-D simulations[3,6] conducted near the density limit and fueled by strong neutral particle injection, and we test the predictions of simple models of blob dynamics against our observations. We confirm the first law of blob dynamics:[4,5] that the blob's charge dipole, induced by the curvature drift, drives the blob radially outward via the ExB drift. However, the electrostatic potential at the midplane inferred from sheath boundary conditions[4,5] is much smaller than what is measured and cannot account for the surprisingly high radial blob velocity observed in these simulations. Accordingly we present evidence that the blobs are disconnected from the divertor sheath, which has important implications for blob dynamics.[7]

We observe a strong correlation between potential and electron temperature; the blobs consist of correlated dipole pairs of vorticity (charge), potential, temperature and parallel current closely associated with the density monopole, and it is likely that the temperature and current dipoles originate in disconnection.[7] Constraints imposed on blob theory by the 3D simulations will be discussed.

* Work supported by US DOE grant DE-FG03-97ER54392 and LLNL contract # W-7405-Eng-48.

1. S. J. Zweben et al., Nucl. Fusion **44**, 134 (2004).
2. X. Q. Xu et al., Bull. Am. Phys. Soc. **48**, 184 (2003), paper KP1-20.
3. D. A. Russell et al., Bull. Am. Phys. Soc. **48**, 184 (2003), paper LP1-71.
4. S.I. Krasheninnikov, Phys. Lett. A **283**, 368 (2001).
5. D. A. D'Ippolito, J. R. Myra and S. I. Krasheninnikov, Phys. Plasmas **9**, 222 (2002).
6. X. Q. Xu et al., New Journal Phys. **4**, 53.1 (2002).
7. D. A. D'Ippolito et al., this conference.
8. J. R. Myra et al., this conference.

Transport and bootstrap current in a small aspect ratio torus

David Gates, Roscoe White
Plasma Physics Laboratory, Princeton University, P.O.Box 451, Princeton, New Jersey 08543

Calculations of collisional thermal and particle diffusivities in toroidal magnetic plasma confinement devices order the toroidal gyroradius to be small relative to the poloidal gyro-radius, i.e $\rho_{i_\phi} << \rho_{i_\theta}$ where $\rho_{i_\phi} \equiv m_i v_{th_i}/qB_\phi$ and $\rho_{i_\theta} \equiv m_i v_{th_i}/qB_\theta$. This ordering is central to what is usually referred to as neoclassical transport theory[1]. This ordering is incorrect at low aspect ratio (with aspect ratio $A \equiv R/a$, where R is the major radius of the torus and a is the minor radius), where it can often be the case that $\rho_{i_\phi} > \rho_{i_\theta}$. This means that excursions of a particle from its nominal flux surface are much larger than estimated in neoclassical theory, with a consequent increase in both radial transport and bootstrap current. We calculate the correction to the particle and thermal diffusivities at low aspect ratio by comparing the diffusivities as determined by a full orbit code[2] (which we refer to as omniclassical diffusion) with those from a gyro-averaged orbit code[3] (neoclassical diffusion). In typical low aspect ratio devices such as the National Spherical Torus Experiment [4] [5] the omniclassical diffusion can be up to 2.5 times the calculated neoclassical value, and the bootstrap current also larger than neoclassical values, with the ratio of bootstrap currents approximately equal to the square root of the ratio of the diffusivities. We discuss the implications of this work for low aspect ratio magnetic confinement experiments.

[1]F. L. Hinton and R. D. Hazeltine, Rev. Mod. Phys., **48** 239 (1976)
[2]R. B. White, L. Chen, Z. Lin, Phys. Plasmas **9** 1890 (2002)
[3]R. B. White and M. S. Chance Phys. Fluids **27**, 2455 (1984)
[4]Y-K. M. Peng and D. J. Strickler, Nucl. Fusion **26**, 769 (1986)
[5]M. Ono, S. M. Kaye, Y. -K. M. Peng, *et al.*, Nucl. Fusion **40**, 557 (2000)

1C47

Nonlinear Resistive Wall Simulations

H.R. Strauss[1],W. Park[2], S. Jardin[2], J. Breslau[2], A. Pletzer[2],L. Sugiyama[3],R. Paccagnella[4]
[1]New York University, New York, New York
[2]Princeton University Plasma Physics Laboratory, Princeton, New Jersey
[3]MIT, Cambridge, MA
[4]Istituto Gas Ionizzati del C.N.R., Padua, Italy

Time dependent nonlinear 3D simulations are being carried out which depend on resistive wall effects. The studies include the deposition of halo current during disruptions, damping of toroidal flow by magnetic error fields, and nonlinear resistive wall modes. The M3D code includes resistive wall boundary conditions, which match the solution inside the resistive wall to the exterior vacuum solution. The exterior problem is solved with a Green's function method, using the GRIN code [2]. Source terms model a "virtual casing" to provide resistive equilibrium, and toroidally varying source terms are used to impose error fields. The M3D code has a time dependent self consistent resistivity model, and realistic geometry including the magnetic separatrix. Thermal conductivity in the presence of the separatrix provides an adequate temperature contrast between the core and the halo region, which is the open field line region outside the separatrix. Initial equilibria are initialized using EQDSK data. A parallel viscosity model has been introduced in M3D to provide dissipative coupling needed for resistive wall modes, as well as for toroidal flow damping. The model conserves toroidal angular momentum, and is consistent with equilibria with toroidal flow in which the equilibrium angular frequency is a flux function. When external magnetic perturbations are applied, the parallel viscosity causes a damping of the toroidal flow energy. Work is also in progress on the resonant amplification of error fields by stable resistive wall modes [3]. Studies are also continuing on the deposition of halo current on a resistive wall during disruptions. The aim to find the toroidal peaking factor and halo current fraction associated with different types of disruptions, including disruptions induced by magnetic error fields.

Acknowledgements: This work was supported in part by the U.S.D.O.E.

[1] Park, W., Belova, E.V., Fu, G.Y., Tang, X.Z., Strauss, H.R., Sugiyama, L.E., Phys. Plasmas 6, 1796 (1999).
[2] http://w3.pppl.gov/rib/repositories/NTCC/catalog/Asset/grin.html
[3] Garofalo, A.M., Jensen, T.H., and Strait, E.J., Physics of Plasmas 10, 4776 (2003).

1C48

Electromagnetic Turbulence Modification of Neoclassical Transport*

F.L. Hinton, R.E. Waltz, and J. Candy

General Atomics, P.O. Box 85608, San Diego, California 92186-5608

Abstract

Electromagnetic turbulence affects plasma transport not only through the standard explicit turbulence mechanisms (E×B and magnetic flutter) but through a modification of neoclassical transport. This is because, in the ensemble-averaged drift kinetic equation, quadratic field fluctuation terms appear in addition to the standard equilibrium gradient and average parallel electric field driving terms.

Previously (APS03) we evaluated the parallel current density driven by these quadratic fluctuation terms using results from the GYRO code. We found that the driven current density has positive peaks on low-order rational surfaces, whose widths are a few ion gyroradii, and whose peak values are comparable to or larger than the Ohmic current density, for the DIII-D L-mode plasma which was studied. The peak current densities driven by turbulence were predicted to be much larger than the Ohmic current density in ITER-sized plasmas, assuming gyroBohm scaling of the turbulence.

Expressions for the radial electron energy flux have also been derived. In addition to the standard neoclassical and explicit turbulence terms, {integrals containing $v_D F$ and $\left[\tilde{v}_E + v_{\parallel}\left(\tilde{B}_x/B\right)\right]\tilde{f}$, respectively} and the turbulent ion-electron energy exchange, we find a turbulence-driven modification of the neoclassical energy flux. From our experience with turbulence-driven parallel currents, we expect that, near low order rational surfaces, the new energy flux may be larger than the standard neoclassical energy flux driven by the Ohmic electric field, for the DIII-D parameters considered previously, and should be much larger for ITER parameters. Thus, the new energy transport mechanism may cause fluxes which are comparable to or larger than the standard turbulence driven energy fluxes. Like the turbulence-driven parallel current density, it should be possible to evaluate the new energy flux using results from the GYRO code.

Expressions for the radial flux of toroidal angular momentum have also been derived. These include explicit turbulence driven fluxes, the standard neoclassical flux and a turbulence-driven modification to the neoclassical momentum flux. It should also be possible to evaluate these using results from the GYRO code.

* This was work supported by the U.S. Department of Energy under Grant DE-FG03-95ER54309.

Gyrokinetic Theory of Mirror Instability

Hongpeng Qu, Liu Chen, Zhihong Lin
Physics and Astronomy Department of university of California, Irvine CA 92697-4575

Magnetic mirror instability is the slow magnetosonic wave driven unstable by the anisotropic pressure in collisionless plasmas. It plays an important role in low frequency magnetic turbulences in high-β space plasmas, e.g., the Earth's magnetosheath, and also potentially in high-β laboratory mirror or dipole plasmas with large fraction of trapped particles. A quasi-hydrodynamic analysis of kinetic mirror instability in non-Maxwellian plasmas recently found that the maximum growth rate increase swith perpendicular wave number until the perpendicular wavelength becomes comparable to the ion gyroradius[1]. Therefore, the finite Larmor radius effects are important in determining the threshold and the wavelength of the kinetic mirror instability.

In this study, we extend the kinetic theory for mirror instability to the short wavelength regime using the gyrokinetic theory to treat finite Larmor radius effects. Following the gyrokinetic formulation of Ref.[2], we have developed a general dispersion relation of the mirror mode with finite Larmor radius effects and arbitrary distribution functions. In the long wavelength limit of $k_\perp \rho_i = 0$, we recover the results of Ref.[1]. In the short wavelength limit, we find that the finite $k_\perp \rho_i$ has stabilizing effects. The coupling to the slow sound wave is also found to be stabilizing.

This work is supported by a DOE Junior Faculty Development Awards DE-FG02-03ER54724, Doe Grant DE--FG03-94ER54271 and NSF Grant ATM-9971529.

References

[1]: O. A. Pokhotelov, R. A. Treumann, R. Z. Sagdeev, M. A. Balikhin, O. G. Onishchenko, V. P. Pavlenko, and I. Sandberg, J. Geophys. Res. VOL 107, NO. A10, 1312, 2002.
[2]: L. Chen, A. Hasegawa, J. Geophys. Res. 96,1503,1991.

1C50

EXTENDED FLUID MODELS AND THEIR IMPLICATIONS FOR SIMULATION ALGORITHMS

D. D. Schnack
Science Applications International Corp., San Diego, CA

D. C. Barnes
University of Colorado, Boulder, CO
and Coronado Consulting, Santa Fe, NM

C. R. Sovinec
University of Wisconsin, Madison, WI

and
The NIMROD Team

Any attempt to model correctly the dynamical behavior of modern laboratory plasmas must include extensions that capture the effects of separate ion and electron fluids and finite ion Larmor radius to the usual resistive MHD model. This is true for alternative concepts (in particular the FRC and the RFP) as well as for tokamaks. These extensions include the Hall and electron pressure gradient terms in Ohm's law and the gyro-viscous stress in the momentum equation. For tokamaks, models for the neo-classical contributions to the ion and electron stress tensors should also be included. In this paper we present a systematic study of the proper form of these equations in different parameter regimes. Only a few dimensionless parameters appear in the coefficients of the two-fluid equations if they are suitably normalized.. Fluid models valid in different parameter regimes emerge by ordering these parameters as large or small compared to the normalized ion Larmor radius. In addition to the usual ideal and resistive MHD models, these include Hall MHD, which incorporates the Hall term but not the ion gyro-viscous stress, and drift MHD, which incorporates the gyro-viscous stress and neo-classical stresses, but only the parallel electron pressure gradient survives in Ohms law. The modifications to Ohm's law in both the Hall and drift MHD models introduce dispersive normal modes (the whistler wave for the case of Hall MHD, and the kinetic Alfvén wave for drift models) that do not appear in ideal or resistive MHD. In addition, the Braginskii form of the gyro-viscosity introduces independent dispersive modes that come from the ion dynamics. While these dispersion relations can be derived by taking the proper limits of the underlying kinetic theory, they are not often discussed within the context of fluid models. Each of these dispersive modes can lead to severe time step restrictions that may impede the ability of numerical algorithms to model long time scale plasma dynamics. We describe several semi-implicit approaches for removing these severe simulation constraints, and report progress in their implementation.

Broken Symmetry in Neoclassical Transport Theory

Yong Xiao and Kim Molvig
Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139

Abstract

A formulation of Neoclassical transport theory is given that is consistent with the traditional formulation and yet has broken "Onsager" symmetry[1] for conjugate terms involving the electron heat flux and bootstrap currents. This is demonstrated for the electron Lorentz transport model for the purely collisional theory. Such a symmetry breaking has been previously suggested[2] but the argument invoked turbulence effects. The terms involved in the present theory are not the ones discussed in the previous work. We show that the symmetry can be mathematically restored by adding certain reactive flow terms to both the Ohmic heating and the electron heat flux, but such an artifice does not represent a clear picture of physical reality (it requires adding non-dissipative terms from the collisionless bootstrap current to the Ohmic heating). We claim that the non-symmetric formulation gives the clearest picture of physical reality, i.e. Neoclassical transport should not be considered an Onsager symmetric theory. The main contribution of the formulation presented is to clarify physically the microscopic processes involved and to distinguish collisionless orbit effects (like the Ware pinch and certain banana-diamagnetic bootstrap current terms), which do not have Onsager symmetry from collisional processes that do. Such understandings are important, we claim, as theory is applied in more complex geometries and extended to include turbulence and collisions in combination.

[1] L. Onsager, Phys. Rev. **37**, 405(1931); **38**, 2265 (1931).
[2] K. Molvig, L. M. Lidsky, K. Hizanidis, and I.B. Bernstein, Comm. Mod. Phys.Part E **7**, 1134 (1982).

Statistical Analysis of ITG Turbulence*

W.M. Nevins, B.I. Cohen, A. Dimits, and D. Shumaker
U. Cal. Lawrence Livermore Nat. Lab., P.O. Box 808, Livermore, CA 94550

Abstract

The fluctuations computed in plasma microturbulence codes are best viewed as a particular realization from an underlying turbulent ensemble. Benchmarking between codes can be achieved by comparing realization-independent characterizations of the turbulent fluctuations, such as the fluctuation spectra, correlation functions, and thermal transport coefficients. Results from the global particle code, GTC, and continuum code, GYRO, are compared with each other and with results from the flux-tube particle code, PG3EQ, and continuum code GS2 in order to benchmark the gyrokinetic codes within the Plasma Microturbulence Project (PMP). We examine parameter scans about the Cyclone test case in which a suite of gyrokinetic particle and gyrofluid simulation codes undertook the same three-dimensional simulation of electrostatic ion-temperature-gradient (ITG) turbulence in a tokamak plasma using physical parameters matching those in an General Atomics Doublet III-D (DIII-D) high-confinement (H-mode) shot #81499. We find significant but not full agreement among the PMP codes.

The self-consistent potential observed in microturbulence simulations can be separated into a flux-surface-averaged piece, $\langle\phi\rangle$, and the deviations from the flux-surface-average, $\delta\phi \equiv \phi-\langle\phi\rangle$. The flux-surface-averaged piece, $\langle\phi\rangle$, does not play a direct role in transport because it can only generate flows within a flux surface. However, $\langle\phi\rangle$ does play an important role in determining the saturated intensity of the ion-temperature-gradient (ITG) fluctuations, $\langle\delta\phi^2\rangle$. We characterize the intensity of the ITG turbulence by evaluating it on a cut through the outboard mid-plane, $\langle\delta\phi^2(r,\theta=0,\zeta,t)\rangle_\zeta$, where $\theta=0$ labels the outboard mid-plane of the tokamak and ζ is the toroidal angle. The two-point correlation functions and power spectrum of $\delta\phi$ are computed using data from all PMP codes and found to be remarkably similar, showing little variation with either the code employed in the simulation or with system size

The ITG thermal transport χ_i and fluctuation intensity $\langle\delta\phi^2\rangle_\zeta$ exhibit intermittency. The heat transport comes in bursts, or "storms" which appear to propagate in radius. Using GKV we observe that χ_i is nearly proportional to $\langle\delta\phi^2\rangle_\zeta$. Figure 2(a) shows the radial variation in the time-average of χ_i from a a/ρ-scan of simulations using the GYRO global continuum gyrokinetic code (a is the tokamak minor radius while ρ is the ion gyroradius) and shows substantial variation in χ_i, in both radius and with a/ρ. The radial variation in χ_i at large a/ρ can be reproduced within the error bars shown in Fig. 2a in individual runs (reproducing parameters at particular radii) of the flux tube codes, GS2 and PG3EQ; while GTC results for χ_i at large a/ρ lie within about 30% of the GYRO and flux tube results. Figure 2(b) shows the time average of the ratio of χ_i to $\langle\delta\phi^2\rangle_\zeta$. We see that the variation in χ_i associated with variation in a/ρ is almost entirely explained by variation in the turbulence intensity, $\langle\delta\phi^2\rangle_\zeta$. There remains only a weak radial variation in this ratio. A nearly linear relation between the thermal diffusivity and the fluctuation intensity is a prominent feature in the simulations, independent of simulation code.

*The authors gratefully acknowledge the GYRO, GTC, GS2 and GEM teams for the use of simulation data produced by these codes.Work performed at the U.C. Lawrence Livermore National Laboratory under U.S. Department of Energy contract W-7405-ENG-36, and at the other laboratories and universities under U.S. DOE Office of Fusion Energy Sciences contracts and grants. The Plasma Microturbulence Project is a US DOE SciDAC project and acknowledges the use of computer facilities and resources at the NERSC and ORNL computer centers.

Monte Carlo Simulation of Neoclassical Edge Pedestal Formation and Study of Pedestal Scaling Law

C. S. Chang,[1,2] Sunghoe Ku,[2] H. Weitzner,[1]
[1]*Courant Institute of Mathematical Sciences, New York University, New York, NY 10012, USA*
[2]*Korea Advanced Institute of Science and Technology, Daejon 305-710, Korea*

Abstract

Understanding and predicting the edge pedestal behavior in H-mode remains to be one of the most critical issues in ITER Physics. After the turbulence suppression, the plasma transport in the H-mode layer is likely to be neoclassical. However, the neoclassical physics for pedestal plasmas cannot be analyzed by a conventional theory due to steep gradient on the order of thermal ion banana width, ion loss cone near the X-point [1], and the neutral effects.

A massively parallel Monte Carlo guiding center ion code XGC (X-point included Guiding-center Code) is built to study self-consistently the neoclassical transport, orbit loss, and neutral effects in realistic flux surface and wall geometry. XGC is a time-dependent full f code, with conserving Monte Carlo Coulomb collision. A Monte Carlo neutral atom diffusion module is built in for a reliable neutral recycling and penetration dynamics. A continuous heat out flow from the core is modeled in to control the pedestal temperature.

Build-up to a maximal neoclassical pedestal (H-mode shape) from an L-mode shape by the neutral ionization is observed. It is found that the particle source from neutral ionization is balanced by the strong convective particle loss around the X-point to give a distinctive pedestal shape. A stronger neutral ionization raises the density pedestal height, and a stronger heat outflow from the core raises the temperature height. Figure 1 shows a maximal neoclassical edge density pedestal obtained from XGC in a 1 Tesla DIII-D plasma. Agreement with the Tanh-fit (line) is remarkably good. The pedestal width here is about 1 cm, which roughly agrees with the experiments. At higher magnetic field, the pedestal width decreases in proportion to 1/B. XGC shows a strong electric field well developed in the pedestal region.

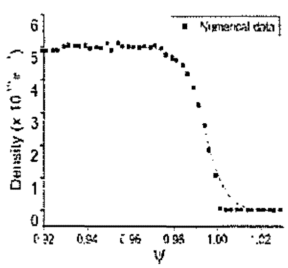


Fig. 1. Neoclassical edge density pedestal with a tanh-fit.

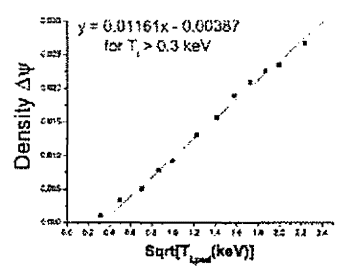


Fig. 2. Density pedestal width in ψ as function of square root of the ion pedestal temperature

Figure 2 shows scaling of the density pedestal width (in ψ) against the square root of the pedestal ion temperature. It shows an offset linear behavior above 300 eV. Similar scaling studies with magnetic field show rather surprising results. The pedestal width does not show a $1/B_\theta$ dependence. But, it rather shows a $1/B_T$ dependence. Thus, the density pedestal width does not scale as the poloidal ion gyroradius! Comparisons with experiments will be presented. Additionally, a positive toroidal momentum source is found at the edge.

Fluid Simulation of Plasma Flow in a Magnetic Nozzle*

Alfonso G. Tarditi

Advanced Space Propulsion Laboratory, NASA Johnson Space Center, Houston, TX (USA)

A magnetic nozzle configuration is determined when a magnetically confined plasma is flowing along diverging field lines. This configuration is particularly relevant for electric propulsion devices that use a plasma as propellant [1-3].

The design of a magnetic nozzle is a critical issue for plasma propulsion as it affects thrust and efficiency. In a properly designed device, the plasma flow modifies and eventually detaches from the magnetic field of the nozzle (carrying some magnetic field with it, similarly to what is observed in the Sun).

The magnetic nozzle topology arises also naturally in the open-field line region of a field reversed configuration (FRC). In FRC and plasma thruster experiments a conducting end plate is typically present (at least on the opposite side of the nozzle), producing shorting of the magnetic field lines and an azimuthal rotation that may affect the flow in the nozzle [4]

To address these issues, a fluid simulation model has been implemented with the *NIMROD* code [5]. The simulations reproduce detachment conditions where a transition from sub- to super-Alfvenic flow occurs. The similarities with a converging-diverging gas-dynamic de Laval nozzle, in which the acceleration from subsonic to supersonic flow is characterized by a transonic "choking" condition at the nozzle throat [6], are discussed.

Simulation runs of the plasma flow pattern in different regimes for a basic de Laval-type magnetic nozzle are presented both for the MHD and for the two-fluid formulation.

REFERENCES

[1] F. R. Chang-Diaz, Scientific American, p. 90, Nov. 2000
[2] E. Y. Choueiri and J. K. Ziemer, Jour. Propulsion and Power, 17 (5), p. 967, 2001
[3] F.R. Chang Diaz. 39th AIAA/ASME/SAE/ASEE, Joint Propulsion Conference Huntsville, Alabama, AIAA 2003-4997, 2003
[4] L. C. Steinhauer, Phys. Plasmas, 9 (9), p. 3851 (2002)
[5] http://www.nimrodteam.org
[6] M. C. Goossens, An Introduction to Plasma Astrophysics and Magnetohydrodynamics, Kluwer Academic, Dordrecht, The Netherlands, 2003

* *Work supported by NASA*

Monday afternoon, April 26

13:30 to 15:30

Doubletree Ballroom

Oral Session 1D

1D01

Extending the Peeling-Ballooning Model of ELMs: Toroidal Rotation and 3D Nonlinear Dynamics*

P.B. Snyder,[1] H.R. Wilson,[2] X.Q. Xu,[3] and D.P. Brennan[4]

[1]General Atomics, P.O. Box 85608, San Diego, CA 92186-5608

[2]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK

[3]Lawrence Livermore National Laboratory, Livermore, CA 94550

[4]Oak Ridge Institute for Science Education, Oak Ridge, TN

The peeling-ballooning model proposes that intermediate wavelength magnetohydrodynamic (MHD) instabilities, driven by the sharp gradients and resulting bootstrap current in the edge barrier region, are responsible for ELMs and impose constraints on the pedestal. Recent studies of linear peeling-ballooning stability [e.g. 1] have found encouraging agreement with observations, both in the onset time and some characteristics of individual ELMs, and in constraints on the pedestal and their variation with a number of parameters.

To allow more detailed prediction of mode characteristics, including eventually predictions of the ELM energy loss and its deposition, we consider effects of sheared toroidal rotation, as well as 3D nonlinear dynamics. A formulation for toroidal rotation shear has been developed and incorporated into the framework of the efficient ELITE stability code [2]. Rotation shear is found to significantly impact the structure of peeling-ballooning modes [Fig. 1(a)], causing radial narrowing and shearing of the mode structure. Studies of the evolution of edge instabilities [Fig. 1(b)] with the 3D nonlinear BOUT code [3] reveal dynamical effects including poloidal narrowing, filamentary structure, and fast radial pulse propagation over a broad region. Use of the extended MHD code NIMROD for ELM simulations is also discussed.

[1] P.B. Snyder *et al.*, Phys. Plasmas **9**, 2037 (2002); Nucl. Fusion **44**, 320 (2004).
[2] H.R. Wilson, *et al.*, Phys. Plasmas **9**, 1277 (2002).
[3] X.Q. Xu, *et al.*, New J. Physics **4**, 53 (2002).

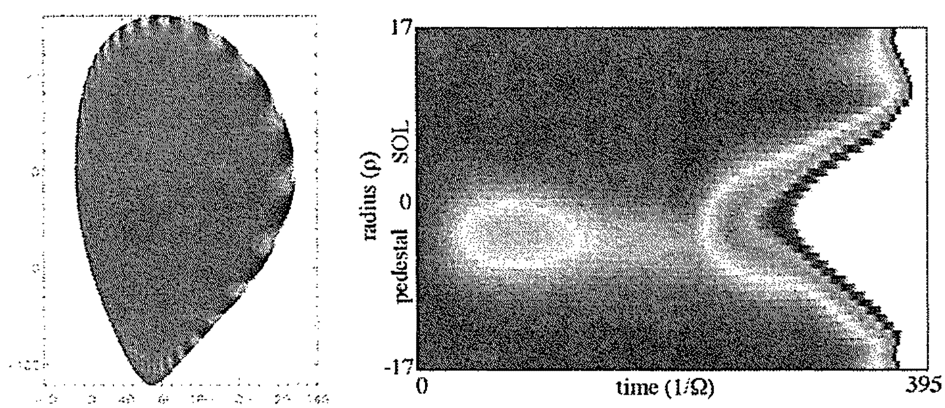


Fig. 1. (a) Calculated structure of an n=11 peeling-ballooning mode in a DIII-D plasma, including the effect of toroidal rotation shear. (b) Time evolution of the perturbed density from a 3D BOUT simulation of an ELM shows initial mode growth in the pedestal region, followed later by a fast pulse extending over a broad radial region.

*This was work supported by the U.S. Department of Energy under Grant DE-FG03-95ER54309, the United Kingdom Engineering and Physical Sciences Research Council, Euratom, and DE-AC05-76OR00033.

1D02

Non-curvature driven modes in the edge pedestal

B. N. Rogers

Dartmouth College, Department of Physics and Astronomy, Hanover, NH

W. Dorland

University of Maryland, College Park, MD

Abstract

We explore the linear stability of simple slab plasma configurations without magnetic curvature using gyrokinetic simulations based on the GS2 code as well as analytic calculations. The configurations, intended to model some of the salient features of the H-mode edge pedestal, are characterized by sheared $E \times B$ flows, strong ion and electron diamagnetic flows that are driven by gradients in the plasma density and/or temperatures, weak collisionality, and finite magnetic shear. Strong parallel flows, though sometimes present in laboratory fusion experiments, are not addressed in this work. We find at least three linear modes of potential importance in such systems: the Kelvin-Helmholz instability, the so-called Tertiary mode, and a non-local driftwave instability. The well-known Kelvin-Helmholz instability is driven by the spatial variations in the $E \times B$ velocity. According to our rough estimates, it is near marginal stability under typical H-mode edge conditions due to the combined stabilizing influence of the magnetic shear and ion diamagnetic effects. The Tertiary mode is an adiabatic, electrostatic mode arising at higher-$k_{\|}$ that is driven primarily by the ion temperature gradient. According to the GS2 simulations, this mode is also near marginal stability in the H-mode edge due to the stabilizing contribution of finite Larmor radius effects. Finally, the non-local driftwave mode is driven by the plasma gradients in conjunction with either electron inertia, electron-ion collisionality, or electron Landau damping. We find this mode is robustly unstable in the presence or absence of magnetic shear at typical H-mode edge discharge levels. Our analysis also suggests that an accurate description of this mode for typical H-mode parameters requires a model that includes electron Landau damping effects, as well as electromagnetic effects and nonlocal profile variations. This mode seems to be a good candidate for driving particle and heat transport in the H-mode edge, in which curvature-driven modes are known to become weak due to diamagnetic stabilization, or in the edge of linear devices.

1D03

A Model of the Radiatively Improved (RI) Confinement Mode in Tokamaks

P. K. Kaw*, R Singh*, A. Rogister+ and V. Tangri*

*Institute for Plasma Research , Gandhinagar – 382 428, India

+Institute for Plasma Physics Forschungszentrum Juelich, D-52425 Juelich, Germany

Abstract

It is well known from impurity seeding experiments in several limiter tokamaks that the plasma may bifurcate into an improved confinement mode, the so called RI mode. In this mode, the confinement improvement is associated with density and temperature peaking and stronger velocity shear. In this paper we propose a novel model for the RI mode. It is demonstrated that radiative effects from impurities distributed in a poloidally asymmetric manner lead to significant density and temperature perturbations on magnetic surfaces. These, in turn, interact with theta dependent toroidal field variations to produce a mean divergence of the stress tensor driving strong toroidal flows. The resulting enhanced toroidal velocity shear on the outer radiative layers produces a stabilizing effect on the instabilities like the drift resistive ballooning mode, drift trapped electron mode and the ion temperature gradient mode. By an investigation of the turbulent particle flux as a function of the density gradient for various values of the radiation asymmetry parameter, it is shown that the plasma can undergo a bifurcation into a better confined peaked density state.

1D04

Dynamics of dust motion in tokamak edge plasmas

S. I. Krasheninnikov[1], Y. Tomita[2], R. D. Smirnov[3], R. K. Janev[2,4], and T. K. Soboleva[5]

[1]*University of California at San Diego, La Jolla, CA 92093, USA*
[2]*National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*
[3]*The Graduate University for Advanced Studies, Toki, Gifu 509-5292, Japan*
[4]*Macedonian Academy of Sciences and Arts, 1000 Skopje, Macedonia*
[5]*UNAM, Mexico D.F., Mexico and Kurchatov Institute, Moscow, Russia*

It has been suggested long time ago [1] that dust particles might be a source of plasma impurities in the early stages of a tokamak discharge. Later on the presence of significant amounts of dust has been observed in the chambers of fusion devices (see for example the review paper [2], and the references therein). The dust particle impact on the performance of current fusion devices has still not been adequately understood [3, 4]. The existence of dust particles in next-step fusion devices, however, may potentially pose a significant safety threat due to the accumulation of hardly containable toxic and radioactive materials retaining tritium [2].

Here we consider some aspects of the dust dynamics in tokamak, and show that transport of dust particles can be an important mechanism of core plasma contamination with impurities. We assume that dust density in a tokamak plasma is rather small so that our consideration is based on a single dust particle motion. Therefore, we ignore the collective phenomena associated with the dust [5]. Similarly as in the studies of dust behavior on the devices with weakly ionized plasmas, a dust particle in a tokamak edge plasma can be confined in an effective potential well formed in the sheath region by the perpendicular components of plasma friction and electrostatic forces. However, unlike those studies, dust particles in a tokamak edge plasma are subject of acceleration by unbalanced large parallel components of the plasma friction force, which appear due to: a) the plasma flow along the shallow magnetic field lines and b) diamagnetic and $\mathbf{E}\times\mathbf{B}$ flows within the magnetized sheath. Therefore, dust particles in tokamak divertor region can be quickly (for ~1 ms) accelerated to the speed $\sim 3\times10^3$ cm/s, which can explain some of the puzzles in Ref. [4]. We demonstrate that the motion of a dust particle along the wall surface, having micro-inhomogeneities, is subject to resonance interactions with particle oscillations in the potential well. As a result, the oscillation amplitude can grow drastically and dust particle can leave the sheath region and fly outside it and, being pushed back by the plasma flow to the wall, bouncing time to time off the surface and further gaining speed by plasma flow acceleration. Finally, the amplitude of particle excursions becomes too large to be pushed back so that dust particle moves to another location at the wall, or flies toward the core plasma. We also report the results of numerical modeling of fast moving dust particles with micro-inhomogeneities of the surface. We consider the limit of strong departures of dust particle from the sheath and compare numerical results with our analytic predictions. Assessment of dust impact on core plasma contamination by impurities shows that: It is unlikely that dust formation on the main chamber wall due to first wall recycling processes can strongly contribute to core contamination. It is, however, quite likely that dust formation in the divertor region, with further dust transport into main chamber, can play significant role in core contamination.

[1] T. Ohkawa, Kaku Yugo Kenkyu **37** (1977) 117
[2] G. Federici, C. H. Skinner, J. N. Brooks, et al., Nucl. Fusion **41** (2001) 1967
[3] D. H. J. Godall, J. Nucl. Materials **111-112** (1982) 11
[4] K. Narihara, K. Toi, Y. Hamada, et al., Nucl. Fusion **37** (1997) 1177
[5] P. K. Shukla, Phys. Plasma **8** (2001) 1791; V. N. Tsytovich, Physics-Uspekhi **40** (1997) 53

Monday afternoon, April 26

15:30 to 17:30

Lewis & Clark Room

Poster Session 1E

1E01

Taylor States in the HIT-SI Experiment

G. J. Marklin

5515 Chesapeake Place, Sugar Land, TX 77479

Abstract

The Helicity Injected Torus (HIT) experiment at the University of Washington has been reconfigured into a high beta spheromak with steady state AC current drive [1]. Helicity is injected by two half torus Reversed Field Pinches (RFP's) connected to the ends of the cylindrically symmetric flux conserver, rotated by 90 degrees from each other. The RFP's are driven with sinusoidally varying voltage and flux. Each side has its voltage and flux in phase, but is 90 degrees out of phase from the other side. The helicity injection rate, which is proportional to the voltage times the flux, goes like $\sin(\omega t)^2$ on one side and $\cos(\omega t)^2$ on the other, making the total injection rate constant in time.

The complex multiply connected 3-dimensional geometry of this device make it difficult to compute anything with existing codes that typically use a structured mesh. This poster will describe a new 3-D Taylor State code that uses an unstructured finite element mesh. The mesh is generated by the code T3D [2], which uses an advancing front method to create a tetrahedral mesh for an arbitrarily shaped 3-dimensional volume from a CAD-like description of a collection of simple surface pieces.

Homogeneous Taylor states are computed by iterating the equation $-\mathrm{del}^2\, \mathbf{A}^{n+1} = \mathrm{curl}\, \mathbf{A}^n$, with under-relaxation. The tangential components of **A** are required to vanish on the boundary. When the fastest growing mode eventually dominates, the amplification factor will be the reciprocal of the Taylor eigenvalue. Inhomogeneous Taylor states are computed by iterating the numerical equation $-\mathrm{del}^2\, \mathbf{A}^{n+1} = \lambda\, (\mathrm{curl}\, \mathbf{A}^n + \mathrm{grad}\, \phi)$, where ϕ is a potential for the externally generated magnetic flux, found by solving Laplace's equation with appropriate jump conditions in the handles. This will converge when λ is below the first homogeneous eigenvalue. For higher values of λ, the homogeneous solution must be projected out during the iteration and then added back in at the end.

Both homogeneous and inhomogeneous Taylor states will be presented for the HIT-SI geometry. Inhomogeneous solutions will be shown for different combinations of fluxes and currents in the two injectors. Field line tracing puncture plots will show the quality of the flux surfaces in each solution presented.

[1] T. R. Jarboe, Fusion Technology **36**, p. 85, 1999

[2] http://power2.fsv.cvut.cz/~dr/t3d.html

1E02

Effect of plasma relaxation and dynamo on mean current and electric field in the reversed field pinches

V.V.Mirnov, C.C.Hegna, S.C. Prager

The University of Wisconsin-Madison, WI 53706
and the Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas

Abstract

Current–driven tearing instabilities are believed to dominate magnetic relaxation and energy transport in configurations such as the reversed field pinch (RFP) and spheromak. In the Madison Symmetric Torus (MST) RFP experiments, the amplitudes of fluctuations in magnetic field $\mathbf{B}^{(1)}$, flow velocity $\mathbf{v}^{(1)}$ and current density $\mathbf{j}^{(1)}$ follow a sawtooth cycle in their time dependence. During the sawtooth crash a surge occurs in the dynamo – a fluctuation-induced mean force in Ohm's law. It is observed that during the crash a substantial change occurs in the mean plasma current density profile and a very large change occurs in the mean electric field profile. We have performed a two-fluid quasilinear dynamo theory to determine how the effect of the dynamo is divided between local current density production and local electric field production. The spatial structure of the fluctuation induced two-fluid dynamo has been studied previously [1]. Both the MHD dynamo ($<\mathbf{v}^{(1)}\times\mathbf{B}^{(1)}>$) and the Hall dynamo ($<\mathbf{j}^{(1)}\times\mathbf{B}^{(1)}>$) contribute to the generalized Ohm's law, $<\mathbf{E}>_{||} - \eta<\mathbf{j}>_{||} = -(1/c)<\mathbf{v}^{(1)}\times\mathbf{B}^{(1)}>_{||} + (1/en^{(0)}c)<\mathbf{j}^{(1)}\times\mathbf{B}^{(1)}>_{||} = \varepsilon_{||}(x, t)$, where $\varepsilon_{||}(x, t)$ is the total electromotive force, < > denotes mean (flux surface average) value, x is the distance from the mode-resonant surface. This equation does not determine $<\mathbf{E}>_{||}$ and $<\mathbf{j}>_{||}$ separately. To calculate these quantities we combine the two-fluid tearing mode theory with a one-dimensional temporal model based on Faraday's law for two cases: (a) $\varepsilon_{||}$ is an exponentially growing tearing mode, (b) $\varepsilon_{||}$ is a periodic function of time with experimentally observed sawtooth temporal profile and a spatial scale x_0. In case (a), the Hall dynamo contributes mainly to the parallel current on a short length scale while the broad MHD dynamo drives the electric field on the scales larger than the electron skin-depth δ. In case (b) at $x_0 >> \delta$, $\varepsilon_{||}(x, t)$ generates mostly a strongly oscillating electric field while a small fraction contributes to a smooth dc current. In the opposite limit, $x_0 << \delta$, all quantities oscillate strongly. In general, the self-inductance of the tearing layer prevents fast changes to the mean parallel current, thus, provides "stiffness" of the profiles with respect to perturbations.

Work supported by U.S.Department of Energy Grant No DEFG02-85E253212 and partially by the NSF Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas.

[1] V.V.Mirnov, C.C.Hegna, and S.C.Prager, Plasma Physics Reports **29** 612 (2003) (Sov. J.Plasma Physics - Fizika Plazmy)

1E03

Stability of resistive wall modes with liquid metal blankets

L.-J. Zheng, M. Kotschenreuther

Institute for Fusion Studies, University of Texas at Austin, Austin, TX 78712

M. S. Chu, M. Chance, and A. Turnbull

General Atomics, P. O. Box 85608, San Diego, CA 92186

Abstract

Resistive wall mode (RWM) stability is investigated in tokamaks with liquid metal (LM) blankets. Fast flowing liquid metal films have been examined as the first wall of a reactor and have been found to significantly stabilize RWMs in cylinder geometry with zero plasma beta and no plasma rotation [1]. Here, equilibria are considered that are very desirable for a reactor, but urgently require stabilization of RWMs: equilibria with high bootstrap fraction, sharp pressure gradients from transport barriers, and strong shaping (Fig. 1). The numerical studies utilized the newly developed AEGIS (Adaptive EiGenfunction Independent Solution) MHD shooting code, which can describe both low- and high-n modes in toroidal geometry for the full MHD equations. The AEGIS code employs Fourier decomposition in the poloidal direction and adaptive mash shooting in the radial direction. A multiple region matching technique is used to handle the numerical difficulty associated with stiff nature of the independent solutions. The n=1 mode structure calculated with AEGIS and GATO codes are shown in Figs. 2 and 3, respectively. Their agreement is very good. Due to its adaptive nature, AEGIS can study MHD modes with smaller growth rate. This can be seen from the sharpness of the mode near the singular layers in Fig. 2. As another feature of the AEGIS code, the wall is taken to have multiple layers and to have finite thickness. The effects of the LM flow speed, injecting direction, the wall position, and the plasma shaping on the RWM stability will be presented.

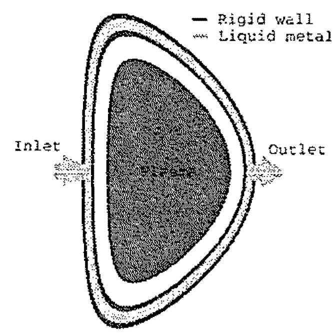


FIG. 1: Equilibrium

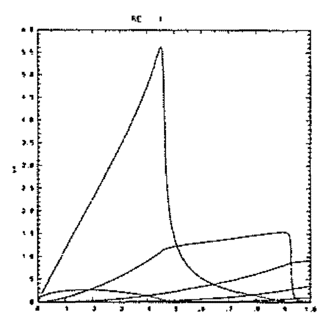


FIG. 2: AEGIS

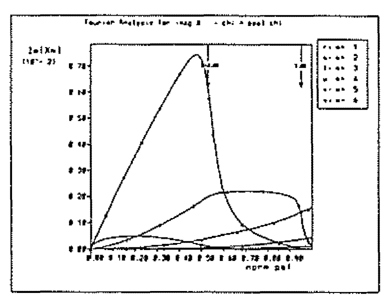


FIG. 3: GATO

[1] J. B. Taylor, J. W. Connor, C. G. Gimblett, and H. R. Wilson, "Resistive wall odes and non-uniform wall rotation", Phys. Plasmas. **8**, 4063 (2001).

[2] L.-J. Zheng, M. Kotschenreuther, A. Turnbull, F. Waelbroeck, J. W. Van Dam, and H. L. Berk, "computation of the MHD modes with rotation and kinetic effects", Bull. Am. Phys. Soc. **48**, 282 (2003).

1E04

Hall-MHD axisymmetric equilibria with flow

G. N. Throumoulopoulos*, H. Tasso†

* University of Ioannina, Association Euratom - Hellenic Republic, Section of Theoretical Physics, GR 451 40 Ioannina, Greece

† Max-Planck-Institut für Plasmaphysik, Euratom Association, D-85787 Garching, Germany

Abstract

The equilibrium of an axisymmetric magnetized plasma is investigated within the framework of the Hall-MHD model with the convective flow term included in the momentum equation for either barotropic equations of state, $P = P(\rho)$ (P and ρ are the plasma pressure and density, respectively), or incompressible flows. For barotropic plasmas the electron diamagnetic term is also kept in Ohm's law. Unlike in the single fluid MHD model, e.g. [1,2], the magnetic surfaces depart from the ion-flow surfaces which coincide with the surfaces of generalized vorticity, $\mathbf{\Omega} = \mathbf{B} + \lambda\nabla \times \mathbf{v}$ ($\mathbf{B}$, $\mathbf{v}$ and λ are the magnetic field, the velocity, and a dimensional constant associated with the Hall term, respectively). The equilibrium is governed by a PDE for the poloidal magnetic flux function ψ coupled with a PDE for the poloidal ion-flow flux function G, two algebraic ψ-integrals and two algebraic G-integrals. For incompressible flows the density becomes constant on the ion-flow surfaces. Several particular cases are examined, i.e."force-free" ($\mathbf{j} \parallel \mathbf{B}$, where $\mathbf{j}$ is the current density), magnetic field aligned-, toroidal-, poloidal-, Beltrami-, and Trkal-flows. Unlike in the single fluid MHD model [1], steady states with incompressible poloidal flows are possible: they are isodynamic-like with pressure varying on magnetic surfaces. Exact solutions can be constructed in the aforementioned particular cases. From the solutions obtained, however, only those with constant density can satisfy boundary conditions pertinent to magnetically confined plasmas; the others exhibit hollow pressure profiles. Also, it is proved that if the flows are parallel to $\mathbf{B}$ they should be incompressible and for isothermal magnetic surfaces they become isodynamic $[B = B(\psi)]$. The latter results indicate that in many cases the Hall term leads to a restriction of the possible equilibria. However, new equilibria can also appear due to the Hall term, e.g. incompressible equilibria with purely poloidal flow.

[1] H. Tasso, G. N. Throumoulopoulos, Phys. Plasmas **8**, 2378 (1998).

[2] G. N. Throumoulopoulos, G. Poulipoulis, G. Pantis, H. Tasso, Phys. Lett. A **317**, 463 (2003).

1E05

Characteristics of tokamak edge-plasma turbulence from 3D simulations*

T.D. Rognlien, M.V. Umansky, X.Q. Xu,
R.H. Cohen, W.M. Nevins, and D.D. Ryutov

University of California Lawrence Livermore National Laboratory
P.O. Box 808, Livermore, CA 94551 USA

Abstract

Edge-plasma turbulence plays key roles in determining when the edge pedestal can form, and in the amplitude and distribution of plasma fluxes to divertors and walls. We report on simulations using the 3D BOUT fluid code [1] as applied to present-day divertor tokamaks. BOUT is unique in spanning the magnetic separatrix, thereby including both the pedestal region and the scrape-off layer (SOL). Two aspects of the turbulence are focused on here. The first topic is the correlation between midplane turbulence and that in the divertor leg begun in Ref. 2. Detailed analysis with the GKV diagnostic package shows that the correlation is weak on flux surfaces very close to the separatrix, but partially returns on outer flux surfaces. This effect is anticipated based on magnetic shearing of the flux tube near the X-point. The shearing can produce an effective resistive layer near the X-point, driving both midplane modes and divertor-leg modes [3]. The relation between these modes and the BOUT results will be discussed. The second topic is an examination of the character of the turbulence during evolution of the density profile owing to a particle source from neutrals that can lead to a density pedestal. The turbulence in these long-running cases is characterized by a reasonably steady fluctuation level, punctuated by occasion bursts that originate in the pedestal region and appear to propagate into the SOL. The nature and possible origin of these bursts will be discussed.

---

*Work performed under auspices of US DOE by University of California Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48 and is partially supported by LDRD project 03-ERD-009.

[1] X.Q. Xu, R.H. Cohen, T.D. Rognlien, and J.R. Myra, Phys. Plasmas **7** (2000) 1951.

[2] M.V. Umansky, T.D. Rognlien, X.Q. Xu *et al.*, Contrib. Plasma Phys., to be pub.

[3] D.D. Ryutov and R.H. Cohen, Plasma Phys. Contr. Fusion, to be pub.

1E06

Density Threshold for Edge Poloidal Flow Generation*

N. Daniels,[1] A. S. Ware,[1] D. E. Newman[2], and C. Hidalgo[3]

[1] *University of Montana, Missoula, MT 59812*
[2] *University of Alaska-Fairbanks, Fairbanks, AK 99775*
[3] *CIEMAT, E-28040, Madrid, Spain*

A numerical transport model is used to examine a density threshold for the onset of an edge poloidal velocity shear layer in toroidal devices. This work is inspired by recent experimental results from the TJ-II stellarator which indicate a critical density threshold for the development of an edge poloidal velocity shear layer [1]. Edge shear-flow layers are commonly observed in toroidal confinement devices, even in L-mode discharges. The numerical transport model has been used to examine internal transport barriers and front propagation of internal transport barriers [2]. The transport model couples together density, ion temperature, electron temperature, poloidal flow, toroidal flow, radial electric field, and a fluctuation envelope equation which includes a shear-suppression factor. In this work, we present results from a series of cases using parameters that are typical of TJ-II discharges. We also present results for a ramp up of the density with a focus on the impact of the ramp on the generation of edge poloidal velocity.

*This work is supported by the U.S. DOE under grant No. DE-FG02-03ER54699 at the University of Montana.

[1] C. Hidalgo, M. A. Pedrosa, L. Garcia, and A. Ware, "Direct experimental evidence of coupling between sheared flows development and increasing in level of turbulence in the TJ-II stellarator", submitted to Phys. Rev. Letters.
[2] D. E. Newman, B. A. Carreras, D. Lopez-Bruna, P. H. Diamond, and V. B. Lebedev, Phys. Plasmas **5**, 938 (1998).

1E07

Equilibrium Reconstruction in Stellarators: V3FIT.

James D. Hanson[1], Steven P. Hirshman[2], Stephen F. Knowlton[1], Lang Lao[3], and Edward A. Lazarus[2].

[1] *Physics Department, Auburn University, Auburn, AL 36849*
[2] *Oak Ridge National Laboratory, Oak Ridge, TN 37831*
[3] *General Atomics, San Diego, CA 92186*

Abstract

The V3FIT code will perform fast, accurate equilibrium reconstruction for stellarators. The EFIT [1] code is the most widely used tool for axisymmetric equilibrium reconstruction. EFIT returns information about the plasma position, flux surface shape and radial profiles as the discharge evolves. It is used for equilibrium control, and input for comparisons with MHD stability and confinement predictions. As beta values and currents in stellarators increase, accurate reconstruction of experimental stellarator equilibria is needed. The V3FIT code will satisfy this need.

The equilibrium reconstruction (ER) will use signals from experimental diagnostics to constrain an MHD equilibrium so that the signals computed from the equilibrium are as consistent as possible with the observed signals. One portion of the ER problem is to compute the expected diagnostic signal, given an assumed MHD equilibrium. Diagnostics could include flux loops, magnetic probes, Thomson scattering and motional Stark effect. For magnetic diagnostics, we have written two codes, V3RFUN and V3POST, that efficiently compute expected diagnostic signals [3]. The two codes are currently being used to design magnetic diagnostic coil sets for the CTH and NCSX experiments.

To be most useful for experiments, the V3FIT code will need to a) run rapidly, b) be flexible, and c) be extensible. For the ER to be rapid, the evolution of the equilibrium parameters toward their true values will need to be tightly coupled to the iterative equilibrium solution. Currently, efforts are concentrated on the VMEC equilibrium solver, which is the most widely used 3D equilibrium code.

We have implemented a loosely coupled (meaning that each set of equilibrium parameters requires an evaluation of a completely converged VMEC equilibrium) ER capability using the STELLOPT code. The STELLOPT ER capability will help the V3FIT code effort with algorithm testing and comparison.

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

[1] L.L. Lao, et al, Nucl. Fusion **25**, 1611 (1985).
[2] S. P. Hirshman and D. K. Lee, Comput. Phys. Commun. **39**, 161 (1986).
[3] S. P. Hirshman, E. A. Lazarus, J. D. Hanson, S. F. Knowlton, and L. L. Lao, Phys. Plasmas **11**, 595 (2004).

1E08

Hybrid Kinetic-MHD Simulations in General Geometry

Charlson C. Kim†, Carl R. Sovinec†, and Scott E. Parker‡
and
The NIMROD Team
†University of Wisconsin, Madison, ‡University of Colorado, Boulder

Abstract

The dynamics of fusion plasmas lead to instabilities that can spontaneously erupt and degrade confinement and sometimes lead to catastrophic disruptions of the entire plasma itself. These instabilities occur in a broad range of spatial and temporal scales, spanning many orders of magnitude, often resulting from nonlinear interactions. Computational simulations are crucial to understanding these phenomena.

NIMROD (Non-Ideal MHD with Rotation - Open Discussion)[1] is a massively parallel three dimensional magnetohydrodynamic simulation utilizing finite elements (**FE**) to represent the poloidal plane and a Fourier decomposition in the toroidal direction. The use of finite elements allows flexibility in the representation poloidal domain. This flexibility of cross sectional domain allows **NIMROD** to model realistic axisymmetic plasma device accounting consistently accounting for the geometry.

To expand the physics capabilities of **NIMROD**, kinetic effects have been added through a δf PIC (Particle-in-Cell) module[2]. This kinetic contribution enters through the MHD momentum equation as an addition kinetic pressure[3]. The addition of kinetic particle effects captures wave-particle interactions that are essential in the accurate modeling of internal kink modes, sawtooth, fish bone instabilities, and toroidal Alfven eigenmodes.

This poster will detail the δf PIC implementation in **NIMROD**, paying particular attention to the parallel scaling and performance. Recent recoding has produced a $\sim 20\%$ improvement in performance and some gains in parallel scaling. We will present several validation test to show the accuracy of particle trajectories and their deposition onto the FE grid. We demonstrate the hybrid kinetic-MHD capabilities through several benchmark cases including Landau damping of compressional Alfven waves and stabilization of the internal kink mode and excitation of the fish bone mode. We then present some preliminary hybrid resistive internal kink studies.

[1]C.R. Sovinec, et.al. "Nonlinear magnetohydrodynamics simulation using high-order finite elements," JCP., in press

[2]C.C. Kim, et.al.," Hybrid Kinetic-MHD Simulations in General Geometry", CPC, pending publication

[3]C.Z. Cheng, JGR 96, (1991)

1E09

Equilibrium and stability of rotating plasmas in a mirror geometry *

James B. Aydemir[1] and Ahmet Y. Aydemir[2]

[1] *Westwood High School*
12400 Mellow Meadow Drive
Austin, TX 78750
[2] *Institute for Fusion Studies*
The University of Texas at Austin
Austin, TX 78712

Plasma flows of significant magnitude seem to be a ubiquitous feature of confined plasmas. The flow by itself, or in combination with the shear in the flow profile, is now recognized to have a stabilizing influence on large scale instabilities such as the resistive wall and internal kink modes in tokamaks, and microturbulence. Long before the beneficial effects of these incidental flows were discovered, flows driven externally as in integral part of a confinement scheme were also examined[1]. Recently some of these ideas have been revived, as in the centrifugal confinement experiment MCT[2] of Maryland and the magneto-Bernoulli experiment of FRC[3]. Both use a mirror field in conjunction with a radial electric field to drive large cross-field flows. We have done a systematic study of the MHD equilibrium and stability of these configurations. Although we have easily found centrifugally confined detached states, our stability calculations have consistently yielded negative results. The expected shear stabilization of the interchange modes is observed for rotation frequencies comparable to the growth rate of the flute modes. However, centrifugal confinement becomes effective at much higher frequencies, where a plethora of ideal MHD modes are observed, both with $k_{\|} = 0$, and with finite $k_{\|}$. These rotationally-driven modes are observed even in a pure θ−pinch configuration without the unfavorable curvature of the mirror fields. Therefore, accessibility of these detached states look highly questionable, although we are continuing with our efforts.

[1] B. Lehnert, Nucl. Fusion **11**, 485 (1971).

[2] R. F. Ellis, A. B. Hassam, S. Messer, and R. B. Osborn, Phys. Plasmas **8**, 2057 (2001).

[3] H. Quevedo, P. M. Valanju, and Roger D. Bengtson, Bull. Am. Phys. Soc. **47**, 67 (2002).

*Work supported by U.S. Department of Energy Contract No. DE-FG03-96ER-54346.

1E10

Extended MHD calculations with high order-of-continuity finite elements

Stephen C. Jardin

Princeton University Plasma Physics Laboratory
P.O. Box 451, Princeton, NJ, 08543

Abstract

The majority of recent magnetic fusion MHD applications using high-order finite elements have utilized elements of the C^0 class in which continuity of the function across element boundaries is imposed, but not continuity of derivatives. [1,2] Here, we describe some features and advantages of using high-order C^1 elements that are constructed so as to have the first derivatives continuous across element boundaries. The high order-of-continuity leads to smaller rank matrices, with similar sparseness patterns, compared to C^0 elements of the same order-of-accuracy, and also allows it to be used on differential operators up to fourth order. These occur, for example, in the viscosity operator in the vorticity equation, or in the hyperresistivity operator in the magnetic flux equation. The fact that it can be directly applied to high-order operators eliminates the need for auxiliary variables in many cases, which in turn leads to even smaller rank matrices. These features make high-accuracy fully implicit solutions of the multi-dimensional extended MHD equations feasible. Examples are presented with a particularly attractive triangular C^1 element with h^5 accuracy. [3] The integrations to form the matrix elements are all done in closed form, even for the nonlinear terms. Applications are illustrated for elliptic problems, anisotropic diffusion, the Grad-Shafranov-Schlüter equation, and the two-dimensional time-dependent MHD and extended MHD equations.

Request oral

[1] C. R. Sovinec, A. H. Glasser, G. A. Gianakon, et al, "Nonlinear MHD simulations using high-order finite elements", J.Comput. Phys. (in press, 2004)
[2] A. H. Glasser and X. Tang, "The SEL macroscopic modeling code", Comput. Phys. Comm., to appear 2004
[3] S. C. Jardin, "A triangular Finite Element with first-derivative continuity applied to Fusion MHD Applications", PPPL-2931 Princeton Plasma Physics Laboratory (February 2004)

1E11

Large Scale Convective Structures and Instabilities in Edge Plasmas

A. I. Smolyakov[1], S. I. Krasheninnikov[2], G. Q. Yu[2], and P.H. Diamond[2]

[1]University of Saskatchewan, Saskatoon, Canada
[2]University of California at San Diego, La Jolla, CA, USA

There is growing body of the experimental evidence that suggest that fast radial plasma transport in the tokamaks scrape-off layer is associated with large scale coherent structures (blobs) that separate from the main plasma and move radially outward. These structures with relatively small cross-field dimensions and extended along the magnetic field have plasma density that significantly exceeds the background plasma density in the scrape-off layer. Similar structures have also been observed in other devices, such as linear plasma machines. It was suggested earlier [1] that the blob motion is a specific form of plasma convection due to the electric field resulting from strongly non-uniform plasma polarization in the edge region. In this work we discuss basic mechanisms of plasma polarization and determine characteristic parameters of associated large scale convective structures. In general, plasma polarization can be caused by the plasma pressure force in the inhomogenous magnetic field [1], by the inertial force (polarization current) due to the time evolution and non-uniformity of the transverse flows [3], or by the action of the external forces such as neutral wind pressure [2]. For a uniform temperature case, the sheath effects have important stabilizing influence thus limiting the size of the structures, however for $\nabla T \neq 0$ they may provide additional destabilizing effects. We find that the magnetic field line bending seriously constrains the transverse blob motion, however fast electron thermal motion along the magnetic field lines largely removes it because the magnetic field becomes frozen into the electron component while the ion (mass) flow is decoupled from the magnetic field. A small residual non-divergent-free part of the difference between the transverse ion and electron velocities determines the parameters of the polarization field. We have also analyzed the possibility of the self-polarization of large scale structures due to the small-scale instabilities via the Reynolds stress mechanism. The development of the secondary, small scale instabilities at the blob-background plasma interface appears to be a further selection mechanism limiting the maximal size of the convective structures. Nonlinear simulations of these instabilities [4] show that large scale blobs disintegrate via sequence of states similar to the nonlinear stages of the Raleigh-Taylor instability in an unstably stratified fluid.

It is expected that the convective blob structures are also strongly inhomogeneous in the axial direction (along the magnetic field). We show that these configurations are subject to the robust axial shear instability. This electromagnetic instability has a significant growth rate (of the order of the characteristic transverse convective frequency, V/δ, where is the convective velocity and δ is the characteristic length scale across the magnetic field. The further, nonlinear evolution occurring on a longer, ion sound time scale, leads to the redistribution of the plasma density within the blob.

[1] S. I. Krasheninnikov, Phys. Lett. A **283**, 368 (2001)
[2] A. I. Smolyakov, S. I. Krasheninnikov, and P.H. Diamond, EPS 2003.
[3] S. I. Krasheninnikov and A. I. Smolyakov, Phys. Plasmas **10**, 3020 (2003)
[4] G. Q. Yu and S. I. Krasheninnikov , Phys. Plasmas **10**, 4413 (2003)

Electromagnetic Electron Temperature Gradient Modes in a Tokamak

Varun Tangri*, Raghvendra Singh and Predhiman Kaw

Institute For Plasma Research, Bhat, Gandhinagar 382 428. India

Abstract

Electromagnetic Electron Temperature gradient (ETG) driven turbulence is now widely recognized as a possible mechanism for small-scale turbulence associated with electron heat transport in tokamaks. Experimental observations such as scaling of threshold temperature gradients [1,2] with plasma parameters, profile resilience and intermittent [3] nature of heat transport are all consistent with linear and nonlinear characteristics of the ETG mode. Experimentally relevant transport has also been observed in nonlinear, toroidal gyrokinetic simulations [4] of the electron temperature gradient instability.

In this paper, we examine the linear features of collisionless electromagnetic ETG mode including effects due to charge non-neutrality, impurity seeding, non-adiabatic ion and impurity response, and finite plasma beta. Modifications of the ETG mode due to coupling with both parallel (compressional) and perpendicular (flutter) perturbations are included. Starting with Braginskii two fluid equations, we derive a differentio-algebraic system, which is solved numerically using finite difference and collocation methods. Comparisons are also made between the earlier linear gyro-kinetic theory and our new analytical semi-local / nonlocal fluid theory results especially highlighting the effects observed on transport. We demonstrate that thresholds obtained from elaborate gyrokinetic simulations or expensive experiments can be satisfactorily explained by simple linear fluid theory as well.

Nonlinear features of the ETG instabilty have also been investigated using the anstaz of scale separation. A Wave kinetic formalism is adopted wherein the short scale ETG modes interact with the long scale streamers. Effects of charge non-neutrality are explored.

[1] Hoang G. T., Bourdelle *et. al.*, Phys. Rev. Lett., **87** 125001 (2001).
[2] Horton W., Zhu P., *et. al.*, Phys Plasmas 7 1494 (2000).
[3] Tangri V., *et. al.*, Phys. Rev. Lett., **91** 025001 (2003).

* email: varun@ipr.res.in

1E13

Analytical and numerical study of the lower-hybrid-relevant wave equation in a toroidal plasma

A. Cardinali and F. Zonca

Associazione EURATOM-ENEA sulla Fusione, Centro Ricerche Frascati, c.p. 65, 00044 Frascati, Italy

An analytical study of the two-dimensional wave equation, which describes the lower hybrid wave propagation in tokamak plasmas and general magnetic field equilibrium, has been performed by means of a multiple spatial scale approach, based on the Poisson Summation formula. This technique is strictly related with that discussed earlier in Ref. [1] and, when applied to plasma instabilities, reduces to the well-known "ballooning formalism" [2]. In applying this formalism, the starting equation for the scalar potential in the cold plasma limit reduces to two nested one-dimensional equations: the first governs the wave structure along the magnetic field lines, while the second describes the slow radial dependence of the wave envelope, for which the usual WKB asymptotic technique is applied. This mixed WKB-full-wave approach can be entirely justified on the basis of spatial scale separation in the radial direction and, for waves that have parallel group velocity faster than in the perpendicular direction (e.g. the lower hybrid wave). Choosing η as the dual variable to $qR_0k_{||} = m + nq$ with respect to the Fourier transform (where q is the safety factor, R_0 is the major radius of the torus, $k_{||}$ is the parallel wave-vector, and m and n are, respectively, the poloidal and toroidal mode number), i.e., as a dimensionless coordinate along the magnetic line of force, a 1D ordinary differential equation (ODE) for the scalar potential in η−space is derived and numerically solved. The operator $\theta_k = k_r/nq'$, acting on the envelope amplitude $A(r)$ can be considered as a parameter (the normalized radial wave-vector). When solved, the 1D ODE along the field line coordinate yields a local dispersion relation connecting r with the normalized radial wave-vector , which can be solved numerically. The wave dynamics in the radial direction is determined by a system of two ordinary differential equations (ray tracing) for the position and the radial wave-vector, whose Hamiltonian function is the previously determined dispersion relation. The system of ray tracing equation describes the WKB evolution of the envelope and, for this reason, it could be referred to as envelope tracing. Preliminary results from numerical solutions of the full 2D wave equation in a pseudo-toroidal coordinate system are also presented. Here, we use a spectral approach based on the Fourier analysis of the scalar potential in the periodic variables θ and ϕ. The starting partial differential equation (PDE) for the potential is replaced by a system of coupled ordinary differential equations along r, which can be numerically solved by standard methods. The complete solution can be finally obtained by numerical methods based on the Fast Fourier Transform (FFT). Well-known characteristic behaviors of the lower-hybrid wave propagation, such as resonance cones of a Gaussian beam in a cold plasma etc., are studied as benchmarks of the numerical solution.
A discussion of the full numerical solution when compared to the previously described analytical study is also presented.

[1] F. Zonca and L. Chen, Phys. Fluids B5, 3668, (1993)
[2] J. W. Connor, R. J. Hastie and J. B. Taylor, Phys. Rev. Lett. **40**, 396, (1978).

1E14

Exact steady-state reconnection solutions in weakly collisional plasmas

P. G. Watson[1] and F. Porcelli[2]

[1] Center for Magnetic Reconnection Studies, Institute for Fusion Studies, University of Texas at Austin, Austin, TX 78712

[2] Burning Plasma Research Group, INFM and Department of Energetics, Politecnico di Torino, Italy

Abstract

We consider the problem of reconnection in weakly collisional plasmas in the strong guide field limit. In this regime the standard resistive Ohm's law is modified to include electron compressibility and electron inertia effects. Despite the increased complexity of the governing equations we show that analytic steady-state solutions, like those discovered by Craig & Henton [1] for the purely resistive case, can be developed for this new system. The resulting solutions are somewhat richer than those of Craig & Henton and there are various regimes in parameter space to consider where the solutions exhibit very different behavior. We also test the dynamical accessibility of these new solutions by solving the time-dependent problem numerically. In certain regimes we find that the steady solutions are unstable, and we postulate that the onset of instability corresponds to the transition from long thin current sheets observed in collisionally dominated plasmas, to the cross shaped current structures observed in certain types of collisionless plasmas.

[1] Craig, I. J. D. and Henton, S. M., *Astrophys. J.*, **450**, 280, (1995)

This work was supported by the U.S. Dept. of Energy Contract No. DE-FC02-01ER-54652 under the auspices of the program for Scientific Discovery through Advanced Computing

1E15

Global Gyrokinetic Particle-in-cell Simulations with Trapped Electrons*

J. L.V. Lewandowski[1] , Y. Nishimura[2] , W.W. Lee[1] , Z. Lin[2] , S. Ethier[1]
1. Princeton Plasma Physics Laboratory, Princeton, NJ 08543
2. Department of Physics & Astronomy, University of California at Irvine, Irvine, CA 92697

The treatment of electron dynamics in global, toroidal, gyrokinetic Particle-in-Cell (PIC) codes represents a major challenge. As it was recently demonstrated, it is physically[1,2] and computationally[3] meaningful to follow dynamically only the nonadiabatic part of the electron response. This approach, however, requires the global solution of a Poisson-like equation for the so-called polarization field[1], $\chi \equiv \partial\Phi/\partial t$, where Φ is the electrostatic potential. The overall viability of the scheme depends crucially on the efficiency of the solution of the Poisson-like equation for χ. To address this issue, a finite-difference based matrix A is generated and the inversion of $A\mathrm{x} = \mathrm{b}$ (where the number of unknowns is typically in the range of $N \in [10^5 - 10^7]$) is carried out using the PETSC[4] library routines. A complementary approach based on the finite element method can also be used to perform the inversion of A (Y. Nishimura *et al*; this conference). An algebraic multigrid (AMG) solver from the hypre[5] library is used as a preconditioner for the matrix A. The elliptic solver is compatible with the parallel structure of the GTC code[6]. Preliminary results of ITG turbulence with trapped electrons will be reported.

* Work supported by US Department of Energy.

[1] J.L.V. Lewandowski, *Phys. Plasmas* **10**, 3204 (2003).
[2] I. Manuilskiy and W. W. Lee, *Phys. Plasmas* **7**, 1381 (2000).
[3] J.L.V. Lewandowski, *J. of Scientific Comp.* (in press; 2004).
[4] http://wwww-unix.mcs.anl.gov/petsc/petsc-2
[5] http://www.llnl.gov/CAS/groups/casc-sag.html
[6] Z. Lin, T. S. Hahm, W. W. Lee, W. M. Tang, and R. White, *Science* **281**, 1835 (1998).

1E16

Ion heating by collisional damping of tearing modes

S.C. Prager, V.A.Svidzinski, V.V.Mirnov,

The University of Wisconsin-Madison, WI 53706
and the Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas

Abstract

Strong self-heating of ions is observed in the reversed field pinch (RFP). For example, during a sawtooth crash the ion temperature can spontaneously triple in ~100 μs. Large-scale tearing instabilities have long been considered to underlie plasma relaxation and dynamo processes in the systems with magnetic self-organization such as the RFP and spheromak. In the Madison Symmetric Torus (MST) RFP experiments, the amplitudes of magnetic and flow velocity fluctuations are characterized by the periodic sawtooth peaks in their time dependence. The heating may arise from tearing instabilities due to irreversible transfer of kinetic flow energy into heat caused by ion-ion collisions. The standard viscous stress tensor calculations are not applicable for high temperature plasmas because the ion-ion collision time ν_{ii}^{-1} is larger than the tearing mode growth time γ^{-1} and the characteristic time of sawtooth crashes. To treat this regime, we employ a hot dielectric tensor in tearing mode theory. We applied the formalism to calculate the absorption rate of a wave in plasma. For the case of interest, $\nu_{ii} \ll \gamma$, $v_{Ti} \ll \gamma / k_{\parallel} \ll v_{Te}$ the ion-ion collisional corrections to the dielectric tensor are found from the Fokker-Plank kinetic equation by a perturbation method while the electron absorption is negligible [1]. Even rare (in comparison with the growth rate) ion-ion collisions lead to a significant anti-Hermitian part of the dielectric tensor that may explain fast ion heating during the sawtooth events. The mode amplitude used in the analysis corresponds to the experimentally measured value of the magnetic field fluctuations in MST and the radial profiles of different field components are found from numerical analysis. For the case of purely growing tearing modes and localized eigenfunctions, the rate of ion heating is comparable to that observed in the MST experiments. The heating rate is proportional to the square of the ion Larmor radius such that it is strong in the low magnetic field configurations. We also analyze the effectiveness of this mechanism in comparison with ion heating based on parallel and perpendicular viscosities, and magnetic pumping in a time varying guide field.

Work supported by U.S.Department of Energy Grant No DEFG02-85E253212 and partially by the NSF Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas.

[1] A. F. Aleksandrov, L. S. Bogdankevich, A. A. Rukhadze, Principles of plasma electrodymamics, Springer-Verlag, New York, 1984

1E17

Water Bags and Contour Dynamics

P.J. Morrison[1] and G.R. Flierl[2]

[1]Department of Physics and Institute for Fusion Studies
University of Texas at Austin, Austin, TX 78712

[2]Center for Meteorology and Physical Oceanography
MIT. Cambridge, MA 02139

Abstract

The water bag model and contour dynamics are examples of reductions of the Vlasov-Poisson and two-dimensional Euler fluid-like equations, respectively. Both are based on initial conditions with the dynamical variable being constant in a certain region. Both equations have Hamiltonian form in terms of a noncanonical Poisson bracket, a realization of an infinite-parameter Lie Algebra that is sometimes called a Lie-Poisson bracket. The derivation of the water bag model and contour dynamics and their associated Hamiltonian form by reduction will be reviewed. Formulations for both nonconvex and convex contours will be given, the former being of general mathematical interest apart from plasma physics and fluid mechanics applications. Applications of the formalism will be presented, including low mode truncations for the description of drift waves or quasigeostophic barotropic vortex dynamics and the calculation of V-states, rigidly rotation vortex states that are claimed to be exact solutions.

Summit Framework: Gyrokinetic calculations of ITG turbulence in general toroidal geometry*

Jean-Noel Leboeuf[1], Viktor Decyk[1], Andris Dimits[2], Dan Shumaker[2]
[1] University of California, Los Angeles, CA 90095
[2]Lawrence Livermore National laboratory, Livermore, CA

Abstract

The Summit Framework[1] is a gyrokinetic particle-in-cell turbulence simulation environment written in Fortran90 providing a unified object-based facility for sharing common components in a massively parallel setting. The Summit Framework is part of the US Department of Energy SciDAC Plasma Microturbulence Project. Work is under way to include kinetic electron models and electromagnetic effects[2], realistic magnetic geometry and global extent under one software environment. General geometry, realistic equilibria capabilities are being incorporated in the Summit Framework through the pg3eq_nc module, itself an extension of the circular geometry pg3eq module[3]. These modules use quasi-ballooning coordinates to solve the three-dimensional, toroidal, delta-f, gyrokinetic equations for ions in order to model ITG turbulence in the electrostatic limit with adiabatic electrons. Realistic geometry is introduced through an interface to data from the EFIT equilibrium code[4]. Massively parallel implementation has been effected using MPI. Successful nonlinear comparisons for a sample shaped and finite beta equilibrium have yielded equivalent results between serial, one-processor and multi-processor parallel implementations. Linear and nonlinear tests are currently under way between the general geometry and circular geometry modules with a circular equilibrium which can be accommodated in both modules. Results from all of these tests will be reported, along with progress in the upgrade of the interface to equilibrium data and in strategies for the global extension of both the circular and general geometry modules.

[1] http://www.nersc.gov/scidac/summit/
[2] Y. Chen, S. E. Parker, B. I. Cohen, A. M. Dimits, W. M. Nevins, D. Shumaker, V. K. Decyk, J. N. Leboeuf, "Simulations of turbulent transport with kinetic electrons and electromagnetic effects", Nuclear Fusion, Fusion **43**, 1121-1127 (2003). Online at stacks.iop.org/NF/43/1121
[3] A. M. Dimits, T. J. Williams, J. A. Byers, and B. I. Cohen, "Scalings of Ion-Temperature-Gradient-Driven Anomalous Transport in Tokamaks", Physical Review Letters **77**, 71-74 (1996).
[4] http://fusion.gat.com/efit/

*This work is performed for USDoE by Univ. California LLNL under contract W-7405-ENG-48 and by UCLA under grant DE-FG02-04ER54740.

1E19

Unresolved Issues in the Simulation of H-mode Pedestal and ELMs in Tokamaks*

G. Bateman[1], A.H. Kritz[1], T. Onjun[1], A. Pankin[2], I Voitsekhovitch[3], and S. Snyder[1]

[1] Lehigh University Physics Department, 16 Memorial Dr. E., Bethlehem, PA 18015, USA
[2] SAIC, San Diego, CA 92121, USA
[3] Present address: Euratom/UKAEA Fusion Association, Culham Science Center, Abingdon, Oxon, OX14 3DB, UK

Abstract

There are a number of unresolved issues related to the integrated modeling of the H-mode pedestal and Edge Localized Modes (ELMs) in tokamaks. The objective of the integrated modeling simulations is to predict the height, width, and shape of the pedestal as well as the frequency and consequences of the periodic ELMs that occur in most H-mode discharges.[1,2,3,4] The following are among the unresolved issues: (1) If all of the anomalous transport were completely suppressed in the pedestal, the effect of the remaining neoclassical transport would be to produce an electron temperature that is significantly higher than the ion temperature at the top of the pedestal, which is not consistent with experimental observations. Hence, models are being developed in which the anomalous ion thermal transport is reduced more than the anomalous electron thermal transport. (2) During an ELM crash, the diffusion of the current density caused by neoclassical resistivity by itself does not remove the pedestal current density fast enough to stabilize the current-driven peeling mode in simulations. There must be fine-scaled magnetic reconnection to remove the pedestal current density on the time scale of an ELM crash, which is less than a millisecond. (3) A model is needed for integrated simulations in which a significant part of the pedestal current is transferred to the wall during an ELM crash, rather than having the pedestal current driven into the plasma during each ELM crash. (4) The models currently used in the integrated simulations do not include the vertical asymmetry effect that is observed in experiments — that it takes less power to make the L to H-mode transition if the X-point of the divertor is in the direction of the ion grad B drift. (5) Plasma blobs, which carry plasma particles and energy to the outboard wall, are not yet included in integrated modeling simulations. These unresolved issues will be discussed together with examples of recent integrated modeling simulations of tokamak H-mode plasmas.

---

* Work supported by U.S. DOE Contract No. DE-FG02-92-ER-5414

[1] V. Parail, G. Bateman, M. Becoulet *et al,* Plasma Physics Reports **29** (2003) 539.
[2] G.W. Pacher, H.D. Pacher, A.S. Kukushkin, *et al,* Nucl. Fusion **43** (2003) 188-195.
[3] T. Onjun, A.H. Kritz, G. Bateman, *et al,* Phys. Plasmas **11** (April, 2004).
[4] A. Pankin, I. Voitsekhovitch, *et al,* American Physical Society Division of Plasma Physics, Oct. 2003.

1E20

Improved Numerical Modeling of Lower Hybrid Experiments in the MST Reversed Field Pinch*

E. Uchimoto[1], J.A. Goetz[2], R. O'Connell[2], S.C. Prager[2], M.A. Thomas[2]

[1]Department of Physics and Astronomy, University of Montana, Missoula, MT 59812

[2]Department of Physics, University of Wisconsin, Madison, WI 53706

Numerical work is under way to improve the modeling of lower hybrid (LH) wave injection experiments in the MST reversed field pinch for electron heating and current profile control in the outer region. This is prompted by recent experimental results including the observation of hard X-ray flux associated with 50-kW RF power launched from an interdigital line antenna in the MST[1]. The suite of codes being used consists of MSTFIT (2-D MHD equilibrium code), GENRAY (generalized ray tracing code) and CQL3D (3-D relativistic, bounced-averaged, quasi-linear, Fokker-Planck code). To increase the realism of the modeling we have incorporated in our Fokker-Planck simulations a radial transport term and a DC electric field term, both consistent with experiments, and an X-ray flux diagnostic routine. We have shown numerically that the LH wave at 800 MHz and $n_{\|} = 8$ is indeed a viable choice for current drive in enhanced confinement discharges with the radial transport coefficient of $3 \sim 5$ m^2/sec. The hard X-ray energy spectrum of 10 keV or higher, however, was not reproduced by CQL3D and awaits an improved modeling of the behavior of the plasma near the antenna. Suggestions will be made to optimize the use of a new antenna which is designed to handle RF power up to 200 kW.

[1] J.A. Goetz, *et al.*, Proceedings of the 15th Topical Conference on Radio Frequency Power in Plasmas (2003), pp. 263-266.

*Work supported by the United States Department of Energy.

1E21

1D Model for Alfvén Cyclotron Instabilities in the Spherical Tokamak Fusion Power Plant

S.E.Sharapov

Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire, UK

Abstract

Identification of possible alpha particle driven instabilities in spherical tokamak (ST) plasmas is one of the important problems to be assessed for a fusion power plant based on the spherical tokamak concept [1], which would necessarily operate in high-β (e.g. $\bar{\beta} \approx 60\%$ [1]), high-density regimes with $\beta_\alpha << \beta_i$. It was previously found [2,3] that the instabilities driven by the radial gradient of fast ions, i.e. toroidal Alfvén eigenmodes, chirping modes, and fishbones, become less significant or disappear as β increases. On the other hand, Alfvén cyclotron instabilities (frequency range $\omega \leq \omega_{Bi}$) driven by the energy gradient and/or temperature anisotropy, are less sensitive to β and may become dominant at high β. The existence of weakly-damped compressional Alfvén and shear Alfvén eigenmodes in high β STs is investigated within a 'hollow cylinder' ideal MHD model [4], that essentially uses a high ellipticity limit, $E = b/a \to \infty$, but keeps the large inverse aspect ratio, $a/R \leq 1$. In such a way 2D eigenvalue problem for the waves trapped in a resonating cavity inside the plasma is reduced to a 1D Schrodinger equation with a potential well determined by the magnetic well and by the radial gradient of the plasma density. This equation is solved for typical equilibrium profiles. Weakly-damped discrete eigenmodes are selected then in accordance with the 'weak-damping' condition, $\varepsilon_1(R) \neq N_\parallel^2$, which means absence of the resonant mode conversion (similar to the Alfvén continuum damping at low frequency).

[1] H R Wilson, G Voss, J-W Ahn et al., *The Spherical Tokamak Fusion Power Plant*, 19th IAEA Fusion Energy Conference, Lyon, France, 14-19 October 2002, paper IAEA-CN-94/FT/1-5

[2] M P Gryaznevich, S E Sharapov, Plasma Physaics Controlled Fusion (submitted)

[3] Y I Kolesnichenko et al., Phys. Rev. Lett. 82, 3260 (1999)

[4] V D Yegorenkov, K N Stepanov. 17th EPS, Venice, v.3, p.1207 (1989)

1E22

Separatrix Reconnection and Meanders in the Standard Nontwist Map

A. Apte, A. Wurm, and P.J. Morrison
Physics Department and Institute for Fusion Studies, University of Texas at Austin,
Austin, TX 78712

Abstract

We consider reconnection and bifurcation phenomena in nontwist area-preserving maps, such as those that model magnetic field lines in toroidal plasma devices with reversed shear profiles. The reconnection changes the phase space topology in the vicinity of the central barrier where the twist condition is violated. Its mechanism and relation to transport has been studied extensively in recent years in e.g., [1], [2], [3]. We discuss several exact methods and their numerical implementation for determining the reconnection threshold in parameter space. The reconnection of odd-period orbits gives rise to *meanders* (invariant tori that are not graphs). We demonstrate nested meander structure numerically, and discuss the idea of meander transport.

[1] D. del Castillo-Negrete, J.M. Greene and P.J. Morrison, Physica D **91**, 1 (1996).
[2] S. Shinohara and Y. Aizawa, Prog. Th. Phys. **100**, 219 (1998).
[3] E. Petrisor, Chaos, Solitons and Fractals **14**, 117 (2002).

1E23

Enhancement of the divertor-leg instability by tilting of the divertor plate

D.D. Ryutov, R.H. Cohen

Lawrence Livermore National Laboratory
Livermore, CA, 94551

A very fast instability driven by sheath boundary conditions exists on the open field lines of fusion devices [1]. Its presence is generally not related to the sign of the field-line curvature, although it becomes somewhat faster in the case of unfavorable curvature. In the presence of the X point, potential perturbations cannot penetrate beyond the X point, because of the very strong shear present in this area [2]. A semi-quantitative way of describing this effect in terms of the effective surface resistivity attributed to a "control plane" just below the X point has recently been suggested and a fast instability driven by the sheath boundary conditions and limited to the divertor leg was predicted [3]. The importance of this instability is that it could increase cross-field transport in the divertor leg (and thereby reduce the heat load on the divertor plate) while, at the same time, have a minimum effect on the transport above the X point (and, accordingly, not lead to deterioration of core plasma confinement). We extend the analysis of Ref. 3 to include effects of finite beta and to find conditions for the strongest enhancement of the instability by radial tilting of the divertor plate [3,4]. We provide a list of experimental signatures of the instability: i) phase velocity and wave-numbers of the most unstable modes; ii) correlations between fluctuations of various parameters, including signals from the flush-mounted probes and iii) the differences between fluctuations in the common and private flux regions. This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract # W-7405-Eng-48.

1. H.Berk, D. D. Ryutov. Yu. A.Tsidulko JETP Lett., **52**, 23 (1990); Phys.Fluids, **B3**, 1346 (1991).
2. D.Farina, R.Pozzoli, D. Ryutov. Nuclear Fusion, **33**, 1315 (1993).
3. D. D. Ryutov, R.H. Cohen. "Instability Driven by Sheath Boundary Conditions and Limited to Divertor Legs." To be published in Contrib. Plasma Phys.
4. D.Farina, R.Pozzoli, D. Ryutov. Plasma Phys. Contr. Fusion, **35**, 1271 (1993).

1E24

A Breeder Algorithm for Stellarator Optimization*

S. Wang,[1] A. S. Ware,[1] S. P. Hirshman,[2] D. A. Spong[2]

[1] *University of Montana, Missoula, MT 59812-1080*
[2] *Oak Ridge National Laboratory, Oak Ridge, TN 37831-8070*

In this work, we present initial work towards the development of a breeder optimization algorithm (BA). The BA algorithm combines a global genetic algorithm (GA) with a local Levenberg-Marquardt optimizer (LM) used to refine each generation. The goal of the BA algorithm is to take advantage of the global parameter space search of the evolutionary algorithm while maintaining the efficiency of the LM method. In principle, the primary advantage of evolutionary algorithms such as GA is that they perform a global parameter space search while the steepest descent methods (such as LM) perform a local parameter space search for the optimal configuration. Previously, we presented results which indicated the evolutionary algorithms are more sensitive to the user input than the LM method and that they are also constrained in stellarator optimization by the fact that equilibria do not exist for a large range of parameter space. Here, we present a description of the breeder algorithm and the first results from the application of the breeder algorithm to stellarator optimization.

*This work is supported by the U.S. DOE under grant No. DE-FG02-03ER54699 at the University of Montana.

1E25

The discontinuous Galerkin method applied to SOL transport*

J. C. Wiley, M. Kotschenreuther, P. Valanju
Institute for Fusion Studies, The University of Texas at Austin, Austin, TX 78712

Abstract

The discontinuous Galerkin (DG) method[1] is becoming popular for solving systems of hyperbolic conservation laws

$$\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial \mathbf{F_x}}{\partial x} + \frac{\partial \mathbf{F_y}}{\partial y} = \mathbf{S}$$

because it combines some of the best features of finite element and finite volume methods. The method is distinguished by expanding the fields in basis functions that are polynomials (possibly high order) within elements and discontinuous between elements. Here a two-dimensional nodal Lagrange-polynomial basis[2] is used in which the polynomial degree of each element can be individually set from 1-10. Each element can also be individually refined with no restrictions on hanging nodes. The key to numerical stability and convergence is in the specification of the numerical flux functions which couple the solution between elements and with the boundary. In addition to a hyperbolic conservation law it is frequently useful to solve a coupled elliptic (Poisson) equation. This ability has recently been added which requires the solution of a large linear system in parallel. The DG method requires that a second order elliptic problem[3] be expressed, at least formally, in terms of first order systems. By the appropriate choice of numerical flux functions, these additional variables can be eliminated before the linear system is solved. For these flux functions the method is called a local discontinuous Galerkin method. The reduction comes at the price of creating additional shadow elements in the parallel decomposition so that neighbors and neighbors of neighbors along processor boundaries are shared. We are using PETSc for the linear solve. The time advance is currently explicit (RK) however we have tested an implicit Crank-Nicholson solver on a simple convection problem. We will describe the application this code to the transport of blobs[4][5][6] in the scrape-off-layer (SOL).

References

[1] Cockburn, B., Shu C.-W., J Sci. Comp. **16**, 3, 173-261 (2001)
[2] J. S. Hesthaven, T. Warburton, J. Comp. Phys. **181**, 186-221 (2002).
[3] P. Castillo, SIAM J. Sci. Comput. **24** 2 524-547 (2003).
[4] S. I. Krasheninnikov, Phys. Lett. **283** 368-370 (2001).
[5] D. A. D'Ippolito, et al., Phys. Plasmas **9** 222-233 (2002).
[6] Ghendriah et al.,Nuc.Fusion **43** 1013-1022 (2003).

*Supported by the US Department of Energy grant DE-FG03-96ER54346

1E26

Equilibrium theory of the pressure pedestal in High (H) mode tokamak plasmas*

P. N. Guzdar[1], S. M. Mahajan[2], and Z. Yoshida[3]
[1]Institute for Research in Electronics and Applied Physics
University of Maryland, College Park, MD 20742
[2]Institute for Fusion Studies, University of Texas, Austin, Tx 78712
[3]Graduate School of Frontier Sciences and High Temperature Plasma Center
University of Tokyo,Tokyo 113-0033, Japan

Recently, using two-fluid Hall-MHD equations, Mahajan and Yoshida [1,2] have developed a theory of plasma relaxed states with flow. The theory gave rise to the so-called double-Beltrami states (DB) obtained by the interaction of the magnetic and velocity fields. The present work extends the earlier theory [2] by allowing for non-constant density, which is determined self-consistently by an equation of state, and limits the maximum pressure gradient by the ideal ballooning stability criterion. It is shown that the detailed solution of the DB system with physically meaningful boundary conditions, augmented by the ballooning mode stability condition, determines uniquely the pedestal width and the pedestal height. The theoretically derived expressions for the height and width can be readily cast into forms that are equivalent to the empirical scaling laws currently in vogue. The intrinsic dependence of the pressure pedestal width and height is the ion skin-depth. By using the stability criterion for ideal ballooning modes, it can be expressed in the form involving the poloidal ion-gyroradius. This is therefore very different from the orbit loss theories for which the poloidal larmor radius is the instrinsic scale-length. Furthermore in magnitude the scalesize is found to be larger than the poloidal larmor radius, which is also consistent with observations. The numerical solutions for the non-constant density, indicate that the computed equilibria have both toroidal as well as poloidal flows. Furthermore the edge density and temperature profiles for different "equations of state" have been computed, and those for the adiabatic constant $\gamma=3$, valid for a strongly magnetized plasma, are found to be consistent with observations. The direction of the radial electric field is also inward. The comparison of the theory predictions with data on some of the large machines is very promising.

1. S. M. Mahajan and Z. Yoshida, Phys. Rev. Lett. **81**, 4863 (1998)
2. S. M. Mahajan and Z. Yoshida, Phys. Plasmas **7**, 635 (2000)

*This work was supported by the US Department of Energy under Grant DE-FG02-93ER54197 at UMD and Grant No. DE-FG03-96ER-54346 at IFS, UT

1E27

Sources and Sinks in the Zonal Flow Energy Balance in Tokamak Microturbulence

A.M. Dimits, W.M. Nevins, and D.E. Shumaker

Lawrence Livermore National Laboratory, Livermore CA 94550

Abstract

The relative contributions of various terms to the driving and damping of the zonal flows in toroidal ion temperature gradient turbulence have been investigated using nonlinear gyrokinetic simulations. The simulation diagnostic was discussed and its correctness, in that the implemented terms numerically recover the net rate of change of the zonal flows, was demonstrated previously (A.M. Dimits *et al.* APS-DPP02 meeting). We have applied the diagnostic to cases in the turbulent finite-transport regime. It is found that (1) the zonal flow energy fluctuates about a steady mean level and (2) zonal flow energy is generated primarily through the Reynolds' stress term and dissipated by the transit time damping terms. The source/sink rates of other terms, such as the diamagnetic Reynolds stress, are finite but lower. Issues of the applicability of an analogous diagnostic to experiments are discussed.

Work performed for USDoE by Univ. California LLNL under contract W-7405-ENG-48, and is part of Summit and the USDoE OFES SciDAC Plasma Microturbulence Project.

1E28

Kinetic Ballooning Instabilities in NSTX[1]

C. Z. Cheng and N. N. Gorelenkov

Princeton Plasma Physics Laboratory

Princeton University. P. O. Box 451, Princeton, NJ 08543-0451

The kinetic effects of trapped electron dynamics and ion Larmor radii are shown to give rise to a large stabilizing effect for kinetic ballooning instabilities (KBIs). The stabilizing effect is due to an enhanced parallel electric field and hence a parallel current that enhances the stabilizing field line tension by a factor proportional to the ratio of the total electron density to the untrapped electron density. n_e/n_{eu}. In comparison with the ideal MHD theory. the first stability β threshold for exciting KBI is increased and the second stability β threshold is reduced. For the low aspect ratio National Spherical Torus Experiment (NSTX) n_e/n_{eu} can be much larger than unity and the kinetic stabilizing effect can be significant. We have performed numerical KBI solutions based on a numerical baseline NSTX equilibrium with a weak reverse magnetic shear. The results show that KBIs are stabilized in most radial domain except around the weak reverse shear region ($0.28 < r/a < 0.37$) for the cases with or without temperature gradients. Moreover, in the unstable region the KBI growth rate is much smaller than the ideal MHD ballooning mode growth rate by more than a factor of 10. However, in the presence of energetic ions it is still possible that kinetic ballooning modes can be resonantly destabilized by the fast ions to large growth rates.

[1]This work is supported by US DoE contract DE-AC02-76-CHO-3073

1E29

Closures of the Vlasov-Poisson System

Christopher S. Jones*, Philip J. Morrison
Institute for Fusion Studies, Dept. of Physics, UT Austin

Parametric closures of one-dimensional Vlasov-Poisson are studied through the inclusion of a source. Parameterizations are considered which may be identified with a closed set of moments. The remaining moments are shown to obey constitutive relations which characterize the set of distributions allowed under the closure. These relations are restricted by the symmetries of the system, thus constraining the form of parametric closures which maintain those symmetries. The dynamics of the distribution subject to closure are shown to be Vlasov-Poisson dynamics with a source determined by the form of the closure. Equating this source to zero reveals constraints on closures which exactly reproduce Vlasov-Poisson dynamics, such as water bag models. These constraints are compared with those that arise from the requirement that the Poisson bracket satisfy the Jacobi identity, preserving the Hamiltonian character of the dynamics.

*This work is supported by the U.S. Department of Energy under Contract No. DE-FG03-96ER-54346

1E30

Gyrokinetic Particle Simulation of Spectral Cascade and Energy Dissipation in Magnetohydrodynamic Turbulences

Z. Lin

University of California, Irvine, CA, USA

Random magnetic fluctuations are ubiquitous in space and astrophysical plasmas. Low frequency magnetohydrodynamic (MHD) turbulence is typically driven at large spatial scales, cascades through inertial ranges, and dissipates the energy to the plasmas at smaller scales. The kinetic processes leading to the dissipation of the turbulence energy at small scales, and associated spectral cascade from large to small scales, are not well understood due to the difficulties of kinetic simulations resolving disparate spatial-temporal scales in MHD turbulences. We have developed a 3D, massively parallel, particle-in-cell electromagnetic code to study the energy cascade and dissipation in anisotropic Alfven turbulences. The ion is modeled using the gyrokinetic method and the electron dynamics is treated using a fluid-kinetic hybrid model based on an expansion of the electron response using the electron-ion mass ratio as a small parameter [1]. The rectangular geometry with uniform magnetic field is used to focus on the fundamental physics process. Linear dispersion relation for decaying kinetic shear Alfven waves has been recovered in linear simulations. Nonlinear simulations with energy injection at large scales will be discussed. This work is supported by U.S. DOE Grant No. DE-FG02-03ER54694.

[1] *A Fluid-Kinetic Hybrid Electron Model for Electromagnetic Simulations*, Zhihong Lin and Liu Chen, *Phys. Plasmas* **8**, 1447 (2001).

1E31

Development of the SEL code and its application to the magnetic reconnection problem.

Vyacheslav S. Lukin, Alan H. Glasser, and X. Z. Tang
Los Alamos National Laboratory

Abstract

A new massively parallel three-dimensional spectral/(hp) element [1] code (SEL) [2] is being developed at LANL in order to address several key issues in computational plasma physics – such as the presence of multiple length/time scales and high degree of anisotropy in most plasmas of interest. Second-order adaptive implicit Newton-Krylov time advance and quasi-static evolution of the computational grid to remain approximately parallel to the magnetic field (field-alignment) with perpendicular adaptive mesh refinement are the main tools we propose for resolving those issues. Presently, a two-dimensional (2D) version of the code is operational and is being tested with applications to magnetic reconnection and tokamak edge plasma modeling.

Physical evolution equations are formulated in a simple flux-source form, which allows for great flexibility in physical systems to be modeled by the code. The formulation is also independent of any particular logically rectangular coordinate system one chooses to compute on; subject only to the knowledge of the Jacobian of that coordinate system. This is done both in anticipation of the field-alignment algorithm now under development and to greatly simplify an implementation in any given curvilinear coordinate system.

The code has been tested against several numerical and semi-analytical studies of 2D magnetic reconnection in resistive MHD, Hall-MHD, and EMHD regimes [3], extending the published results where possible. In the near future, we will enhance the physical model to include further two-fluid and pressure tensor effects in order to be able to self-consistently model both microscopic (i.e. detailed structure of localized reconnection sites) and macroscopic (i.e. global evolution of a magnetized plasma) processes, whose interaction is crucial to any astrophysical or laboratory plasmas in which fast magnetic reconnection plays a significant role.

---

[1] G. E. Karniadakis and S. J. Sherwin, *Spectral/hp Element Methods for CFD* (Oxford University Press, New York, 1999).

[2] A. H. Glasser and X. Z. Tang, to appear in Comp. Phys. Comm. (2004).

[3] I. J. D. Craig *et.al.*, Phys Plasmas **10**, 3120 (2003); J. D. Huba, L. I. Rudakov, Phys Plasmas **10**, 3139 (2003); D. Del Sarto *et. al.* Phys. Rev. Lett. **91**, 235001 (2003); Richard Fitzpatrick, Phys Plasmas **11**, 937 (2004).

1E32

Justification of the model for H-mode pedestal and ELMs

A. Y. Pankin[1,2], I. Voitsekhovitch[2,3], G. Bateman[2], A. Dnestrovski[4], G. Janeschitz[5], A. H. Kritz[2], M. Murakami[6], T. Onjun[2], T. Osborne[7], G. W. Pacher[8], and H. D. Pacher[9]

[1]SAIC, San Diego, CA 92121
[2]Lehigh University, Bethlehem, PA 18015
[3]Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
[4]Kurchatov Institute, Russian Federation
[5]FZK-PL-Fusion, Karlsruhe, Germany
[6]Oak Ridge National Laboratory, Oak Ridge, TN 37831
[7]General Atomics, San Diego, CA 92186
[8]Hydro-Québec, Varennes, Québec, Canada
[9]INRS, Québec, Canada

Abstract

A model for the H-mode pedestal and for the triggering of Edge Localized Modes (ELMs) is presented. The model predicts the height, width, and shape of the H-mode pedestal and the frequency and width of ELMs. The model for the H-mode pedestal in tokamak plasmas is based on flow shear reduction of anomalous transport. While the simple model based on the shear flow suppression of the ITG turbulence has been tested before [1, 2], the new model takes into account the fact that different instabilites are suppressed by the flow shear at different rates. In this model, the ion temperature gradient mode, resistive ballooning mode, trapped electron mode, and electron temperature gradient mode have individual flow suppression functions. Turblence driven by these modes contribute to the anomalous thermal transport at the plasma edge. Formation of the pedestal and the L-H transition is the direct result of $E_r \times B$ flow shear suppression of anomalous transport in this model. The periodic ELM crashes are triggered by MHD instabilities. Two mechanisms for triggering ELMs are considered. ELMs are triggered by ballooning modes if the pressure gradient exceeds the ballooning limit or by peeling modes if the edge current density exceeds the peeling mode criterion. The effects of ELM crashes on the H-mode pedestal profiles are discussed. The models for the pedestal and ELMs are used in the ASTRA integrated transport code to follow the time evolution of tokamak discharges from L-mode through the transition from L-mode to H-mode, with the formation of the H-mode pedestal, and, subsequently, to the triggering of ELMs. The reference scenario is based on a DIII-D discharge. Scans with heating power, magnetic field, and plasma density are presented. The resulting dependences are compared with the experimental observations.

---

[1] O. V. Zolotukhin, Y. Igitkhanov, G. Janeschitz, G. W. Pacher, H. D. Pacher, G. V. Pereverzev, G. Strohmayer, and M. Sugihara, in *28th EPS Conference on Contr. Fusion and Plasma Phys. (Funchal, Portugal, June 2001)* (2001), pp. 677–680.

[2] G. Janeschitz, G. W. Pacher, O. Zolotukhin, G. Pereverzev, H. D. Pacher, Y. Igitkhanov, G. Strohmeyer, and M. Sugihara, Plasma Phys. and Controlled Fusion 44, A459 (2002).

1E33

Nonlinear Generalized Master Equations: building a mathematical formalism to describe transport in the presence of critical thresholds

R. Sánchez[1], B.Ph. van Milligen[2] and B.A. Carreras[3]

[1] Universidad CARLOS III, 28911 Leganés, Madrid, SPAIN
[2] Asociación Euratom-CIEMAT, Laboratorio Nacional de Fusión, 28040 Madrid, SPAIN
[3] Fusion Energy Division, Oak Ridge National Lab., Oak Ridge 37831 TN, U.S.A.

In the last few years, it has been often suggested that some of the following elements do probably play a role in setting the dynamics of plasma anomalous transport: collisional diffusion, turbulence, critical thresholds (gradients and/or characteristic lengths), avalanches, self-similarity, non-Gaussian probability distribution functions, long-term temporal correlations, power-laws and self-organized criticality. If this is indeed the case, it may have dramatic consequences on the reliability of the extrapolation of current plasma confinement results to larger devices. In spite of this, most of transport analysis is still done by using sets of transport equations that neglect the importance of these elements, since they are based instead on classical diffusive operators for both density and temperatures that cannot accomodate most of them in a consistent way.

In this work we will present a first step towards building a mathematical framework able of describing transport in a system in which these elements dominate the dynamics [1]. The formalism is based on a nonlinear variation of the well known Continuous-Time Random Walk (CTRW), a concept introduced in the late 50s that have been applied to many problems in Physics and Chemistry. We will show how to derive a Generalized Master Equation (GME) that provides with an ensemble-averaged description of this modified CTRW. We will also show that, in the fluid limit, this GME connects to a description of transport in terms of fractional derivative equations (FDE). The possibilities of building a new class of transport codes based on these tools will be discussed, and some applications to simple systems will be shown.

[1] B.Ph. van Milligen, R. Sánchez and B.A. Carreras, *Probabilistic transport models for transport in fusion plasmas*, in press, Physics of Plasmas (2004).

1E34

Nonlinear physics of laser-irradiated micro-clusters

B. N. Breizman, M. V. Fomyts'kyi, A. V. Arefiev, and C. Chiu

Institute for Fusion Studies, The University of Texas at Austin,
Austin, TX 78712

Abstract

A nonlinear model has been developed to describe self-consistently electron response and ion acceleration in dense clusters that are smaller in size than the laser wavelength. This work is motivated by high-intensity laser-cluster interaction experiments [1]. The theory reveals that the breakdown of quasi-neutrality affects the cluster dynamics in a dramatic way. It produces an ion shell that expands quickly due to its own space charge whereas the central part of the cluster expands at a much slower rate under the thermal electron pressure. Another manifestation of non-neutrality is an anisotropy of the ion expansion. The developed model shows a natural trend for the electron population to have a two-components distribution function [2]: a cold core that responds to the laser field adiabatically and a halo that undergoes stochastic heating [3]. As the ion shell expands, the potential well for the electron core becomes more shallow, producing a leak of the core electrons from the cluster. The coherent response of the cold electron core to the laser field is very similar to that of a nonlinear pendulum driven by an external force. This analogy explains the enhancement of the third harmonic generation observed when the frequency of the applied field is close to 1/3 of the core eigenfrequency. It is essential that the ion background has to be non-uniform or non-spherical to produce a nonlinear electron response [4]. The key predictions of the model have been verified in 3D numerical simulations.

Research is supported in part by the NSF FOCUS center.

[1] T. Ditmire, J. Zweiback, V.P. Yanovsky, T.E. Cowan, G. Hays, and K.B. Wharton, Nature **398**, 489 (1999).

[2] B. Breizman and A. Arefiev, Plasma Physics Reports, 29, 642 (2003)
http://peaches.ph.utexas.edu/ifs/ifsreports/950_Breizman.pdf

[3] F. Brunel, Phys. Rev. Lett. **59**, 52 (1987).

[4] M. V. Fomyts'kyi, B. N. Breizman, A. V. Arefiev, and C. Chiu, *Harmonic generation in clusters* , to be published in Phys. Plasmas.
http://peaches.ph.utexas.edu/ifs/ifsreports/975_Fomytskyi.pdf

ORAL

1E35

Progress towards the development of a linear MHD stability code for axisymmetric plasmas with arbitrary equilibrium flow.

L. Guazzotto[1], R. Betti[1] and J.P. Freidberg[2]

[1] University of Rochester and Laboratory for Laser Energetics, Rochester, NY 14623
[2] Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge MA 02139

Abstract

Fast toroidal plasma flows are routinely induced by neutral beam injection in current tokamaks such as NSXT and DIII-D. These equilibrium flows are beneficial to the overall plasma performance since they stabilize external modes such as the resistive wall mode and suppress turbulence when the flow shear is large enough. Flow and flow shear have also a significant influence on the stability and nonlinear evolution of the internal kink mode and ballooning modes. Theoretical results indicate that improvements in plasma stability usually occur regardless of the flow direction (toroidal or poloidal). Fast poloidal flows are difficult to drive in moderate and low beta plasmas because of the large poloidal viscosity. However, high beta plasmas (with beta of order unity) develop an omnigenous structure that should be optimal for driving large poloidal flows due to the reduced poloidal flow damping. While equilibria with both poloidal and toroidal flows can now be generated with the U. Rochester code FLOW [1], the tools available to tackle the stability problem are quite limited. With the exception of the code MARS [2], none of the available stability codes includes the effects of finite flow. MARS (developed at Chalmers University) includes only toroidal flow and, to the best of the authors' knowledge, it does not include the effects of flow in the equilibrium. With the goal of producing a tool capable of investigating MHD stability with arbitrary flow, we have begun the development of a new linear stability code. The code is based on a recent δW formulation in which the energy principle (including arbitrary flow) is reduced to an eigenvalue problem of the kind $(\omega \mathbf{A}-\mathbf{B})\mathbf{x}=0$. Such a formulation is attractive because it allows a straightforward implementation of the finite element method to determine the elements of **A** and **B**. A finite element code has been developed to solve such an eigenvalue problem. The code is at an early stage and it is currently being tested to study the stability of simple slab equilibrium unstable to the Rayleigh-Taylor and the Kelvin-Helmoltz instabilities. Where possible, analytical solutions have been derived and are compared to the results of the code.

[1] L. Guazzotto, R. Betti, J. Manickam and S. Kaye, Phys. Plasmas **11**, 604 (2004)
[2] A. Bondeson, G. Vlad and H. Lütjens, in Proc. IAEA Technical Committee Meeting on Advances in simulation and Modelling of Thermonuclear Plasmas, June 1992, Montrèal, Canada (IAEA, Vienna, 1993) p. 306

1E36

Numerical Study of the Formation, Ion Spin-up and Nonlinear Stability Properties of Field-Reversed Configurations [1]

E. V. Belova, R. C. Davidson, H. Ji, M. Yamada, Princeton Plasma Physics Laboratory, Princeton; C. D. Cothran, M. R. Brown, Swarthmore College; and M. J. Schaffer, General Atomics, San Diego, USA

Abstract

Results of three-dimensional numerical simulations of the field-reversed configuration (FRC) using the HYM code are presented. Emphasis of this work is on the nonlinear evolution of magnetohydrodynamic (MHD) instabilities in kinetic FRCs [1]. Kinetic simulations show nonlinear saturation of the n=1 tilt mode. The n=2 and n=3 rotational modes are observed to grow during the nonlinear phase of the tilt instability due to ion spin-up in the toroidal direction. The ion toroidal spin-up is shown to be related to the resistive decay of the internal flux, and the resulting loss of weakly confined particles (with small toroidal angular momentum $|p_\phi| = |Rv_\phi - e/m\psi| \ll |\psi_0|$) from the closed-field-line region. Simulations with zero initial ion rotation demonstrate the formation of a rigid-rotor rotation profile in about 60-80 Alfvén times, depending on the plasma resistivity. The peak ion toroidal velocity is proportional to the ion diamagnetic drift velocity, and in the final state, the ions carry large fraction of the total current. The details of the ion toroidal spin-up determine the nonlinear evolution of the rotational instabilities.

Three-dimensional simulations of counter-helicity spheromak merging and the FRC formation show good agreement with results from the SSX-FRC experiment [2]. Simulations show formation of an FRC in about 30 Alfven times for typical experimental parameters. It is demonstrated that a relatively large plasma viscosity ($\mu > 2\,10^{-3}$) and the field line-tying effects can slow-down the reconnection, and are likely to be responsible for the incomplete reconnection of the toroidal field seen in the experiments. Growth rate of the n=1 tilt mode is shown to be significantly reduced compared to the MHD growth rate due to large plasma viscosity and field-line-tying effects. Several factors contribute to further reduction of the instability growth at later time ($t \gtrsim 20t_A$), including the nonlinear effects and the stabilizing effect of the strong toroidal flows (low-viscosity case), and the residual toroidal field (high-viscosity case).

[1] E.V. Belova et al., Phys. Plasmas **11**, in press (2004).

[2] C. D. Cothran et al., Phys. Plasmas **10**, 1748 (2003).

---

[1] Research supported by the Department of Energy Contract No. DE-AC02-76-CHO-3073

1E37

Dynamic parallel viscous force in the low collisionality regime*

A. L. García-Perciante, J. D. Callen, K. C. Shaing and C. C. Hegna

University of Wisconsin-Madison, Madison WI 53706-1609

Some neoclassical effects in toroidal geometries can be illustrated via a simplified 2D bumpy cylinder magnetic field. With this model, we explore the dynamics of parallel flow damping due to the parallel viscous force. A dynamic closure for $\langle \mathbf{B} \cdot \nabla \cdot \Pi \rangle$ is introduced in the parallel momentum equation and the flow evolution is obtained as an integral equation. Long and short times limits are calculated in a large aspect ratio approximation and compared to previous results obtained by other authors [1]. The result is further extended to toroidal geometry and the ambipolarity of cross field fluxes addressed [2].

The closure is obtained as an initial value problem using a Chapman-Enskog-like [3] approach. A Laplace transform to frequency space allows a solution in terms of Cordey eigenfunctions [4] which can be inverted analytically in a small $\sqrt{\epsilon}$ approximation. The expression obtained is time dependent and this allows us to explore the viscous damping at all times. For early stages the evolution is governed by the decay of the initial perturbation as $\partial U/\partial t \sim (\epsilon\nu/t)^{-1/2}$. For longer times, the initial condition is damped and an exponential decay with a decay rate $\nu_p \sim \epsilon\nu$ is obtained. Finally, in steady state the known static result $\nu_p \sim \sqrt{\epsilon}\nu$ is recovered. The poloidal angle dependence of the parallel viscous force in an axisymmetric torus can also be obtained; progress in this direction will be presented. The final expression that we are after, having explicit time and spatial dependences should be useful for numerical codes like NIMROD.

*Research supported by DoE grant DE-FG02-86ER53218.

References

[1] R. C. Morris, M. G. Haines, and R. J. Hastie, Phys. Plasmas **3**, 4513 (1996) and references cited therein.

[2] S. P. Hirshman, Nucl. Fusion **18**, 917 (1978).

[3] J.P. Wang and J.D. Callen, Phys. Fluids B **5**, 3207 (1993).

[4] J. G. Cordey, Nucl. Fusion **16**, 499 (1976).

Drift Ordered Short Mean Free Path Fluid Equations

P. J. Catto[1] and A. N. Simakov[2]

[1] *Plasma Science and Fusion Center, M.I.T., Cambridge, MA. 02139, USA*
[2] *Los Alamos National Laboratory, Los Alamos, NM. 87545, USA*

Abstract

Short mean free path descriptions of magnetized plasmas have existed for almost 50 years. The earliest work by Braginskii [1] in 1957 assumes an ordering in which the ion mean flow is on the order of the ion thermal speed. Mikhailovskii and Tsypin [2] realized that this ordering is not the one of most interest in many practical situations in which the flow is weaker and on the order of the ion heat flux divided by the pressure. In their ordering the ion flow velocity is allowed to be on the order of the diamagnetic drift velocity - the case of interest for most fusion devices in general, and the edge of many tokamaks in particular. Their drift ordering is required to properly retain the temperature gradient terms in the viscosity as well as the terms found by Braginskii. Our treatment [3] corrects the expressions for the ion parallel and perpendicular collisional viscosities found in these later treatments [2] which used an approximate truncated polynomial expression for the distribution function and neglected quadratic heat flow terms associated with the non-linear form of the collision operator. The modifications to the pressure anisotropy and perpendicular collisional viscosity that we evaluate are valid for turbulent and collisional transport, and also allow stronger poloidal density, temperature, and electrostatic potential variation in a tokamak than the standard Pfirsch-Schlüter ordering. We have also evaluated the electron pressure anisotropy and gyroviscosity, and then used the ion and electron equations to obtain a reduced system of equations suitable for edge plasma modelling [4].

Research supported by the US Department of Energy.

1 S. I. Braginskii, Soviet Phys. JETP **6**, 358 (1958) and in Reviews of Plasma Physics, edited by M. A. Leontovich (Consultants Bureau, NY 1965) Vol. 1, p. 205.

2 A. B. Mikhailovskii and V. S. Tsypin, Beitr. Plasmaphys. **24**, 335 (1984) references therein.

3 P. J. Catto and A. N. Simakov, Phys. Plasmas 11, 90 (2004).

4 A. N. Simakov and P. J. Catto, Phys. Plasmas 10, 4744 (2003).

1E39

Dynamics in Time Series: Characterization and Construction

Willis Ferenbaugh[1], D. E. Newman[1], P. W. Terry[2]

[1] U. of Alaska–Fairbanks, Department of Physics, Fairbanks, AK
[2] U. of Wisconsin–Madison, Madison, WI

Abstract

Plasma experiments and models are characterized not only by the specifics of their construction but by the nature of the output they produce. Data streams are examined for statistical or dynamical signatures, and new types of signatures are necessary additions to the descriptive toolbox. The Hurst exponent is a measure of correlations (on all time scales) which has been used to describe the dynamics in various plasma experiments. Rescaled range (R/S) analysis is the original method for finding the Hurst exponent, and this poster further investigates the dynamical information contained in this analysis. To address this issue, techniques to produce synthetic data series with known properties are developed. Well–known algorithms exist for making fractional Gaussian noises, and using these noises, a simple procedure for constructing correlated data with an arbitrary distribution is examined. This is done by very selective rearrangement of a series with the desired distribution. The effects of rearrangement on specific time scales is also examined, shedding light on processes which produce different dynamics on different time scales (which surfaces as different slopes on R/S graphs). Last but not least, there is a continuing effort to distill additional dynamical information with new R/S–like analyses. These new techniques should capture the essence of higher–order spectral analyses: bispectra, trispectra, etc. The hope is that the dynamical properties of a data set can be better/completely described by a hierarchy of Hurst–like measures.

1E40

An analysis of lower hybrid wave diffraction and focusing with a 2D toroidal full-wave code.*

J. C. Wright[1], P. T. Bonoli[1], C. K. Phillips[2], M. Brambilla[3], and E. D'Azevedo[4]

[1]MIT Plasma Science and Fusion Center
Cambridge, MA

[2]Princeton Plasma Physics Laboratory
Princeton, NJ

[3]Max-Planck Institute for Plasma Physics
Garching, Germany

[4] Oak Ridge National Laboratory
Oak Ridge, TN

ABSTRACT

The increased availability of massively parallel processing (MPP) architectures has lead to the improved accessibility of some full-wave phenomena in ultra-short wavelength regimes [1]. In this work, we have modified the dielectric operator of an ion cyclotron range of frequencies (ICRF) full-wave code, `TORIC` [2], to be valid in the lower hybrid range of frequencies (LHRF). These new capabilities permit studies of diffraction and focusing effects at the very short wavelengths of lower hybrid (LH) waves. Results of full-wave LH calculations in the Alcator C-Mod geometry have been obtained (see Fig. 1) and have been compared with ray tracing analysis for the same parameters. Differences between the geometric optics and full-wave models have been found to be related to focusing, diffraction, and spectral broadening effects [3] not included in the eikonal method. These differences will be discussed at length.

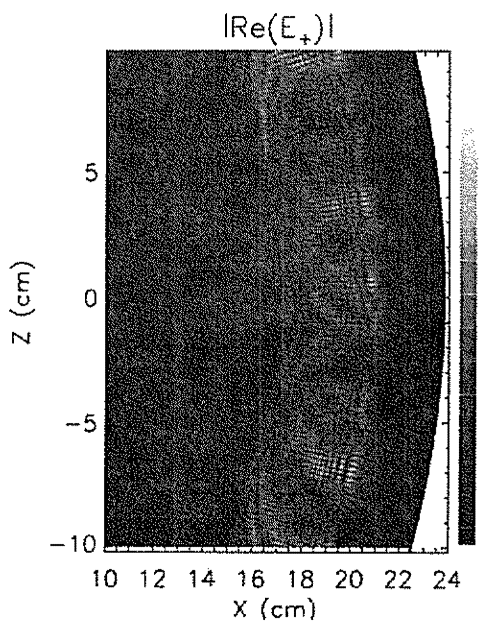


Figure 1. Reflecting lower hybrid slow and fast waves between an edge cutoff and mode conversion surface in the Alcator C-Mod geometry.

[1] J. C. Wright, *et al.*, Phys. Plasmas, accepted for publication Jan 2004.
[2] M. Brambilla, Plasma Phys. Controlled Fusion 41, 1 (1999).
[3] G. Pereverzev, Nucl. Fusion 32, 1091 (1992)

*Work supported by SciDAC and USDOE Contract No. DE-FC02-01ER54648.

1E41

Hamiltonian description of ITG dynamics and coherent structures

F. L. Waelbroeck, P. J. Morrison
Institute for Fusion Studies, University of Texas

The Hamiltonian formalism constitutes an effective framework for investigating the dynamics of fluid models.[1] In particular, it provides techniques for finding conserved quantities, obtaining first integrals of the equilibrium equations, and constructing variational principles describing the stability of nonlinear coherent structures. It can also be used to guide the derivation of fluid closures by specifying the subset of higher order terms that need to be retained in order to preserve desired conservation properties. More recently, the Hamiltonian formalism has been used by Krommes and Kolesnikov to derive equations governing the generation of zonal flow and long wavelength coherent structures under the effect of stochastic forcing by short wavelength modes.

A particularly appealing feature of the Hamiltonian formalism is that it readily provides first integrals of the equations governing the structure and propagation of modons, or solitary waves. Modons usually consist of isolated or paired vortex tubes propagating in the direction perpendicular to both the magnetic field and the equilibrium density gradient. They have been shown to have remarkable resilience. Their properties are generally consistent with the observation in simulations and experiments of patterns of flow or density perturbations that enjoy a lifetime substantially exceeding the correlation time for the turbulence. Such patterns, called coherent structures, are thought to play an important role in turbulent transport. In particular, they give rise to intermittency and non-Gaussian statistics, and they determine the asymptotic behavior of the turbulent spectra. They have been clearly identified in observations of edge turbulence, where their effect on the erosion of plasma-facing components is a source of concern. In the confinement region, coherent structures are responsible for avalanches and have been observed as radially extended coherent signals in the electron cyclotron emission.

Here we construct a Hamiltonian formulation of the equations governing the dynamics of the ion temperature gradient (ITG) instability with finite ion Larmor radius (FLR). We use as a starting point the model of Kim, Horton and Hamaguchi (henceforth KHH) describing electrostatic turbulence driven by the gradient of the ion temperature in slab geometry.[2] We present Hamiltonian formulations for two different versions of the basic ITG model. The first corresponds to a traditional, fully adiabatic response for the electrons and the second to a more accurate parallel adiabatic response where the electron density is insensitive to perturbations that are constant on a flux surface. We derive a complete family of Casimir invariants for our models and use these invariants to construct a variational principle describing the equilibrium and stability of propagating modons. Our solution extends previous descriptions of coherent structures for ITG models by retaining both FLR and parallel flow effects.

Acknowledgements This work was funded by the U.S. Department of Energy Contract No. DE-FG03-96ER-54346.

References

[1] P. J. Morrison, Rev. Mod. Phys. **70**, 467 (1998).
[2] C. B. Kim, W. Horton, and S. Hamaguchi, Phys. Fluids B **5**, 1516 (1989).

1E42

Plasma Beta Enhancement in Reactors from the Thick Conducting Blanket

M. Kotschenreuther, J. Wiley, L. Zheng

Institute for Fusion Studies, University of Texas, Austin TX 78712

Reactor blankets for breeding tritium in a tokamak reactor often have considerable net conductivity, are thick, and are close to the plasma. Here, we give calculations which indicate a strong potential that their stabilizing effect can lead to a doubling of tokamak reactor beta. We give calculations in simplified plasma geometry, but including crucial realistic complexities of the conducting shell provided by a blanket: it is thick, toroidally segmented, non-axisymmetric, and has considerable non-conducting regions. We find that blankets can provide a much better stabilizing shell than the vacuum vessel in present tokamak experiments, and the dedicated shell which has been assumed in reactor studies to date. Approximate calculations indicate that it appears possible to extend the practical elongation of a reactor to between 2.5 and 3, rather than values ~ 2 as has been assumed in the past. Studies for ARIES reactor designs[1] have shown that increasing elongation to this range can enable roughly a doubling of beta for reactor scenarios, but this has been considered impossible before now due to unacceptable engineering requirements for a dedicated stabilizing shell. Our results indicate that a dedicated shell appears superfluous for many blanket designs, and the net conductivity of the blanket can enable such high elongations. Conceptual blanket designs will be examined similar to those which are being considered for the ITER Test Blanket Module program; some are better than others as stabilizing shells. With suitable lamination of the magnet shield it also appears possible for feedback signals to penetrate through the blanket and stabilize resistive wall modes for axisymmtric modes and kink modes (in simplified plasma geometries and models). Thus, both physicists and engineers should recognize that blankets have an unrecognized potential for physics benefits which could significantly improve the attractiveness of fusion reactors. This strongly motivates future studies to quantitatively examine these effects with realistic plasma equilibria.[2]

[1]C.E. Kessel, T.K. Mau, S.C. Jardin, F. Najmabadi, Princeton Plasma Physics Laboratory Report PPPL-3573

2 L.-J. Zheng, M. Kotschenreuther, M.S. Chu, M. Chance, A. Turnbull, this conference

1E43

Generalized Parallel Ion Viscous Stress Tensor in Slab Geometry

M.K. Addae-Kagyah, E.D. Held
Physics Department, Utah State University
Logan, UT 84322-4415

Abstract

An analytical prelude to the NIMROD[1] implementation of the generalized (unified) parallel ion viscous stress[2] is presented in this work. The unified stress closure is cast into geometrically correct form suitable for the study of fluid flow, heat flow and general fluid dynamics, in magnetized plasmas of arbitrary collisionality. In this work, analytical models of plasma flow and temperature evolution, in slab geometry[3], were closed with the unified closure, instead of the Braginskii-type closure. The plasma is modeled as that immersed in slab magnetic islands[4] which may or may not include field line stochasticity. This model of flow and temperature evolution is further reinforced by using the integral parallel heat flow closure[5] in the energy conservation equation. Thus, the complete NIMROD-ready analytical model comprises all the relevant forms of equations, closures and weak forms that would facilitate NIMROD matrix computations, semi-implicit time advance, grid recomputation etc, in slab geometry. The divergence and gradient of the parallell ion sress tensor is derived, and its effects evaluated , within the context of fusion physics. The next logical step, in the future, would focus on implementing this model in NIMROD and performing relevant investigations. In particular, future work would involve NIMROD studies of several paradigms of plasma collisionality (low to high), as well all as various regimes of magnetic field stochasticity, to find out whether unified closures lead to more accurate physical results.

[1]C.R. **Sovinec, et al.,** UW CPTC Report 02-5 (2003)
[2]E.D. Held, Phys. Plasmas **10,** 4708 (2001).
[3]T.A. Gianakon, et al., (Work-in-Progress) (2002).
[4]E.D. Held, J.D. Callen, C.C. Hegna and C.R. Sovinec, Phys. Plasmas **8,** 1171 (2001).
[5]E.D. Held, J.D. Callen, and C.C. Hegna , Phys. Plasmas **10,** 3933(2003).

1E44

Multi-Scale Simulations of ITG and ETG with Sheared Flows

J. H. Kim and W. Horton
Institute for Fusion Studies
The University of Texas at Austin
Austin, Texas 78712

Quasi-two-dimensional pseudo-spectral simulations of ITG-ETG-sheared flow turbulence are presented from model equations with hyperviscosities. Probability distributions functions (PDF) of the vorticity $\omega = \rho^2\nabla^2\phi$ and the filtered vorticity $\zeta = (1-\rho^2\nabla^2)\rho^2\nabla^2 = \sum_1^\infty \rho^{2n}\nabla^{2n}\phi$ are presented for grids up to $(1024)^2$. The PDFs are characterized by heavy tailed PDFs rather than gaussians. We study the turbulence power transfer between wavenumber bands $[k_n, k_{n+1}]$ from restricted sums of $P_n = \sum \boldsymbol{k}_1 \times \boldsymbol{k}_2 \cdot \hat{\boldsymbol{z}}(k_2^2 - k_1^2)\phi_{k_1}\phi_{k_2}\phi_{k_3}$ where the conservation of energy follows from the $\Sigma P_n = 0$. From characterizations of P_n, low-order models of the interaction of W_{ITG}, W_{ETG} and F-shear flow are constructed.

This work is supported by the U.S. Dept. of Energy Contract No. DE-FG03-96ER-54346.

1E45

Neoclassical Parallel Momentum Balance and Flow Damping in Quasi-Symmetric Stellarators

D. A. Spong
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6169

Quasi-symmetric stellarators encompassing the three possible forms of quasi-symmetry: quasi-poloidal (QPS), quasi-toroidal (NCSX) and quasi-helical (HSX) are now either operational or in the planning stages. These different symmetries will allow tests of neoclassical transport physics in a range of three-dimensional toroidal systems whose $|B|$ variation within a flux surface varies from nearly tokamak-like $[|B| \approx |B|(\theta)]$ to mirror-like $[|B| \approx |B|(\zeta)]$. Recently, a fluid moments approach has been developed that provides a more self-consistent way to evaluate the effects of these differing symmetries on both the parallel and perpendicular transport; this is based on a theory[1] that corrects for momentum-conserving and ion-electron frictional coupling effects. We have developed tools to numerically evaluate the viscosities, flow velocities, self-consistent ambipolar electric field, bootstrap currents, and cross-field fluxes of particles and energy based on this moments method approach. The DKES code[2] is first used to generate the monoenergetic particle/energy diffusion, Ware-pinch and neoclassical resistivity enhancement coefficients over a range of collisionality, electric fields and flux surfaces. Velocity integrations and momentum-conserving corrections are then carried out, resulting in a complete transport matrix that takes into account ion-electron coupling effects and provides both the parallel and perpendicular components of transport. This model has been applied to the above stellarator configurations and has indicated a number of interesting effects. For example, in the quasi-poloidal QPS device, poloidal flow-damping can be suppressed by about a factor of 10 relative to equivalent axisymmetric devices. Other examples of application of this model to three different symmetries will be discussed.

Acknowledgements - Work supported by U.S. Department of Energy under Contract DE-AC05-00OR22725 with UT-Battelle, LLC.

---

1 H. Sugama, S. Nishimura, Phys. Plasmas **9**, 4637 (2002).
2 W. I. van Rij, S. P. Hirshman, Phys. Fluids B, **1** (March, 1989).

1E46

Computation of Singular MHD Instabilities with DCON

Alan H. Glasser and Andrei N. Simakov
Los Alamos National Laboratory

ABSTRACT

The DCON code is in wide use for computing the ideal MHD stability of axisymmetric toroidal plasmas. It uses an adaptive numerical integrator to solve a system of ordinary differential equations for the radial dependence of complex Fourier coefficients of the normal displacement, a generalization of Newcomb's equation, from the magnetic axis to the plasma-vacuum interface. Fixed-boundary stability is determined by a toroidal generalization of Newcomb's criterion. Free-boundary stability is determined by the sign of the lowest eigenvalue of the sum of plasma and vacuum response matrices. DCON has been extended to compute the outer ideal region matching conditions for singular modes such as resistive and neoclassical tearing modes. A matching matrix is constructed from asymptotic coefficients of resonant and nonresonant solutions on either side of each singular surface and corresponding terms from any singular surface model. A dispersion relation for growth rates and eigenfunctions is obtained from the roots of the determinant of this matrix.

Two improvements have been introduced recently to make the code more robust, reliable, and accurate. First, the Frobenius expansion about the singular surface, previously carried out to first order in the distance from the singular surface, has now been extended to all orders. This has required systematizing the procedure by means of advanced matrix algebra, which is then used in the actual code. The maximum order used is an input parameter `norder`; it may be automated in the future. Systematically increasing `norder` is shown to produce more rapid convergence and smoother behavior in a scan over toroidal field strength. Finally, a more reliable procedure has been developed to stop the approach to the singular surface at the "sweet spot" where the error is a minimum.

The second improvement concerns the accuracy of the Grad-Shafranov equilibrium solution. DCON has interfaces to 17 different equilibrium codes. For ideal MHD stability, DCON obtains good, clean results for all of them. Resistive stability analysis is found to be much more sensitive to imperfections in the equilibrium, especially in the neighborhood of the magnetic axis. Highly converged and resolved equilibria yield clean results but require impractically long run times with most equilibrium codes. To deal with this problem, a new equilibrium code is being developed, to be incorporated into DCON, specifically to refine the given equilibrium to the standards required for accurate resistive stability analysis, based on the variational moment method.[1]

[1] L. L. Lao, S. P. Hirshman, and R. M. Wieland, Phys. Fluids **24**, 8, 1431 (1981).

1E47

Control and Optimization of the Vacuum Field Configuration in Compact Stellarators

D.J. Strickler, D. del-Castillo-Negrete, and S. P. Hirshman,

Fusion Energy Division
Oak Ridge National Laboratory
Oak Ridge, TN, 37831-6169

The suppression of vacuum magnetic islands due to low order resonances is demonstrated in compact stellarators. Magnetic field lines in stellarators are 1-1/2 degrees of freedom Hamiltonian systems which are in general non-integrable and may exhibit chaos. Of particular interest are magnetic islands which, by resonance overlap, can give rise to chaos that results in poor plasma confinement. Accordingly, it is important for stellarator optimization to develop techniques to control the location and size of islands. In the present work, the magnetic field is due to a set of filamentary stellarator coils, including modular, vertical field, and toroidal field windings. By following magnetic field line orbits in a stellarator symmetric system, periodic orbits of order $m=N/\iota$ (for N-field period symmetry) are located in a toroidal symmetry plane. Following [1], the tangent map is calculated for each periodic orbit (fixed point of the composed return map), and the residues [2], a measure of island size, are targeted in a nonlinear optimization. For prescribed modular coil geometry, major island chains in the National Compact Stellarator Experiment (NCSX) and Quasi-Poloidal Stellarator (QPS) vacuum configurations can be significantly reduced in size by varying only coil currents. These techniques will be used to determine island size [3] in compact stellarators. The optimization will be extended to reduce islands resulting from winding geometry errors in NCSX and QPS by varying the orientation of modular coils in array, e.g., through small shifts and rigid-body rotations.

[1] J.R. Cary and J.D. Hanson, Phys. Fluids **29**, 2464 (1986).
[2] J.M. Greene, J. Math. Phys. **20**, 1183 (1979).
[3] J.R. Cary and J.D. Hanson, Phys. Fluids B **3**, 1006 (1991).

1E48

Quasi-omnigenous tokamak equilibria with fast poloidal flow

B. Hu, L. Guazzotto and R. Betti

University of Rochester and Laboratory for Laser Energetics,
Rochester, NY 14623

Abstract

Macroscopic plasma flow plays an important role in the equilibrium and stability of tokamak plasmas. While fast toroidal flow is routinely generated by neutral beam injections, fast poloidal flow may be difficult to drive because of the inherently large poloidal viscosity of standard tokamak plasmas. The viscous damping is caused by the so-called magnetic pumping due to the variation of the magnetic field strength along the flux surfaces. The poloidal flow damping can be greatly reduced in omnigenous equilibria where the magnetic field strength is approximately constant over the flux surfaces. In the case of tokamak plasmas, such equilibria usually develop for high values of beta (of order unity). High beta equilibria have so far only been investigated in static plasmas where they develop a configuration with magnetic surfaces squeezed against the outboard edge.[1] In the present work, we take advantage of the capabilities of the recently developed equilibrium code FLOW [2] in order to investigate the possibility of generating omnigenous equilibria with fast poloidal flow. Because of the reduced damping, such equilibria should be able to sustain poloidal flow. Two questions arise when fast poloidal flow is introduced: Do omnigenous equilibria still exist? And if so, how do they look like? Using the code FLOW, we were able to derive quasi-omnigenous equilibria with flow velocities greatly exceeding the poloidal Alfvén speed. Interestingly, such equilibria are very different from the static ones since their flux surfaces are squeezed against the inboard edge of the plasma. The inboard shift is induced by the large dynamic forces that far exceed the pressure forces. Possible applications of such equilibria to the Electric Tokamak (ET) [3] are presented and discussed. This work was supported by the US-DOE under contract No. DE-FG02-93ER54215.

[1] S. C. Cowley, P. K. Kaw, R. S. Kelly, and R. M. Kulsrud, Phys. Fluids B **3**, 2066 (1991)
[2] L. Guazzotto, R. Betti, J. Manickam and S. Kaye, Phys. Plasmas **11**, 604 (2004)
[3] R. J. Taylor, J.-L. Gauvreau, M. Gilmore, P.-A. Gourdain, D. J. LaFonteese and L.W. Schmitz, Nucl. Fusion **42**, 46 (2002)

1E49

Collisionless axisymmetric equilibrium with diamagnetic flows*

J.J. Ramos
Plasma Science and Fusion Center, Massachusetts Institute of Technology.
Cambridge MA 02139, U.S.A.

A recently derived system of finite-Larmor-radius collisionless two-fluid equations is used to obtain stationary flow equilibrium relations in axisymmetric toroidal geometry. This model contains a general treatment of the gyroviscous stress, the pressure anisotropy and the anisotropic heat fluxes. The analysis is based on a perturbative expansion in powers of the small ratio between the ion gyroradius and any other characteristic length, $\epsilon \sim \rho_i/l \ll 1$. The flow velocities are assumed to be of the order of the diamagnetic drifts, and therefore are taken to be comparable to the ratio between heat fluxes and pressures and first order relative to the ion thermal speed, $u \sim q/p \sim \epsilon v_{thi}$. Under this ordering, the gyroviscous stress tensor is second order relative to the mean scalar pressure, and includes the gradients of the collisionless parallel heat flux and the diamagnetic perpendicular heat flux together with the more familiar terms proportional to the product of the pressure and the gradient of the flow velocity. In first order, one obtains a generalized Grad-Shafranov equation and specific expressions for the pressures, the density, the electric potential, the flow velocities and the heat fluxes, up to a number of free flux functions. These free flux funcions are determined by the solubility constraints in second order.

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

1E50

Nonlinear wave-particle interaction in helically symmetric stellarators with bumpy fields*

JaeChun Seol and C. C. Hegna
Department of Engineering Physics University of Wisconsin
Madison, WI 53706-1609

In a stellarator with helical ripple, the spatial extent of the local minima in the magnetic field can be of order of the resonant interaction region of applied ECRH waves due to short wavelength $|B|$ variation. In this event, particles trapped in the helical ripples in stellarators bounce back and forth along the magnetic field line, and trapped particles get energy from the wave repeatedly. When the turning points are far from the resonance region, the heating process is stochastic and wave-particle interaction makes a small perturbation on the distribution function. Therefore, quasi-linear theory is valid. However, quasi-linear theory is not valid when the turning points are very close to the resonance region and the particles stay in the resonance region long enough to make several energy excursion caused by relativistic nonlinear wave-particle correlation. When this is the case, the wave and particles are correlated and the stochastic process is not viable. Nonlinear wave-particle interaction for deeply trapped particles has been described in previous work. In this work, the equivalent diffusion operator when nonlinear wave-particle interaction dominates will be derived. It is desired to look for steady-state solution of the Fokker-Planck equation when the heating term and the Coulomb collision term are balanced in order to analyze power deposition and address the role of superthermal electrons on neoclassical transport.

*Research Supported by U.S. DoE under grant no.DE-F02-99ER54546

1E51

Development of a Gyro-kinetic Vlasov Simulation Code for Boundary Plasmas

X. Q. Xu and W. M. Nevins
Lawrence Livermore National Laboratory, CA 94550

A new development of an integrated kinetic simulation code is described to model the boundary region of tokamak fusion reactor plasmas in a realistic magnetic geometry. A kinetic treatment of the edge pedestal is required because the radial width of the pedestal observed in experiment is comparable to the radial width of individual particle orbits (leading to large distortions of the local distribution function from a Maxwellian), while the mean-free-path is long compared to the connection length in the hot plasma at the top of the edge pedestal and becomes short going toward the SOL. Compared to fluid models, the non-linear kinetic formulation we propose to develop adds two velocity-space dimensions to calculate the particle distribution function, which will significantly depart from a Maxwellian in the H-mode pedestal. A Fokker-Planck operator will be used to describe collisional velocity-space transport. This paper is a report on the formulation and numerical implementation of a non-linear kinetic treatment of edge turbulent transport. In particular, we will present a consistent set of equations to describe a kinetic edge plasma on the appropriate time scale while avoiding any ordering of the length-scale of the edge turbulence relative to the equilibrium, turbulence time-scales relative to the collision time. We will report the test results to compare the best available numerical scheme to solve parallel advection with electric acceleration in different coordinate representations in a realistic magnetic geometry. The progress on numerical implementation of Fokker-Planck operator will also discussed.

This work was performed under the auspices of the USDoE by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

1E52

Separate Dynamic Formation, Evolution and Control of Electron Channel Transport Barriers and Ion Channel Barriers

D. E. Newman[1], B. A. Carreras[2], P. W. Terry[3]

[1] Department of Physics, University of Alaska-Fairbanks, Fairbanks AK
[2] Fusion Energy Division, Oak Ridge National Laboratory, Oak Ridge TN
[3] Dept of Physics, Univ. of Wisconsin – Madison, Madison WI

Abstract

Simple dynamical models have been able to capture a remarkable amount of the dynamics of the transport barriers found in many devices[1,2,3], however, an open question which remains is the variable nature of the electron thermal transport channel. It has been found that occasionally an electron channel barrier will form with a standard ("ion channel") barrier, while at other times the electron channel barrier does not form even when a strong "ion channel" barrier forms and finally, electron barriers may sometimes form without a concomitant ion barrier. By adding to the simple barrier model an evolution equation for electron fluctuations we investigate the interaction between the formation of the standard ion channel barrier and the somewhat less common electron channel barrier. Barrier formation in the electron channel is found to be even more sensitive to the alignment of the various gradients making up the sheared radial electric field then the ion barrier. Electron channel heat transport is found to significantly increase after the formation of the ion channel barrier but before the electron channel barrier is formed. This increased transport is important in the barrier evolution and therefore the profile evolutions in the system.

[1] D. E. Newman, B. A. Carreras, D. Lopez-Bruna, P. H. Diamond, and V. B. Lebedev, Phys. Plasmas, 5 (4) 938-952 (1998).
[2] D. Lopez-Bruna, D. E. Newman, B. A. Carreras, and P. H. Diamond, Phys. Plasmas 6, 854 (1999).
[3]E. J. Synakowski, M. A. Beer, R. E. Bell, K. H. Burrell, B. A. Carreras, P. H. Diamond, E. J. Doyle, D. Ernst, R. J. Fonck, P. Gohil, C. M. Greenfield, T. S. Hahm, G. W. Hammett, F. M. Levinton, E. Mazzucato, G. McKee, D. E. Newman, H. K. Park, C. L. Rettig, G. Rewoldt, T. L. Rhodes, B. W. Rice, G. Taylor, M. C. Zarnstorff, Nucl. Fusion 39, 1733 (1999).

Research sponsored by the Office of Fusion Energy Science, U. S. Department of Energy, under Contract DE-FG03-99ER54551 with the UAF Geophysical Institute

1E53

Hybrid Simulations of Alpha Particle effects on the Interal Kink Mode in ITER*

J. Chen, G.Y. Fu, J. Breslau, W. Park

Princeton Plasma Physics Laboratory, Princeton, NJ

The effects of fusion alpha particles on the n=1 internal kink mode is studied by using particle/MHD hybrid simulations with the M3D code[1]. For parameters and profiles of ITER, simulations show that the n=1 internal kink is not stabilized by fusion alpha particles at the central safety value of $q(0) = 0.7$. The numerical results will be compared with simple analytic results to understand the q profile dependence of alpha particle stabilization as well as effects of finite orbit width and role of passing alpha particles.

References

[1] W. Park, E.V. Belova, G.Y. Fu, X.Z. Tang, H.R. Strauss, L.E. Sugiyama, Phys. Plasmas **6** 1796 (1999)

*Supported by DOE DE-AC02-76-CHO-3073.

Tuesday morning, April 27

8:30 to 9:30

Doubletree Ballroom

Review Talk 2A

2A01

Astrophysical Dynamo Action

Fausto Cattaneo
Dept. of Mathematics
University of Chicago

Dynamo action describes the sustained conversion of kinetic energy into magnetic energy within the bulk of an electrically conducting fluid. It is commonly invoked to explain the origin of astrophysical magnetic fields.

Since its inception in the first half of the last century, dynamo theory – the mathematical description of dynamo action – has grown into a substantial body of work. In this talk, I shall review the present state of dynamo theory in astrophysics; the extent to which it succeeds in explaining the origin of cosmic magnetic fields, and what open issues remain.

I shall introduce several different dynamo scenarios that differ in underlying physics, and mathematical structure. In particular I shall discuss large- and small-scale dynamo action, fast and slow dynamos, and dynamos driven by both rough and smooth velocity fields.

In each case I will emphasize which issues arise from the linear (kinematic) part of the dynamo problem and which arise from the non-linear aspects of dynamo generation.

Tuesday morning, April 27

9:30 to 10:00

Doubletree Ballroom

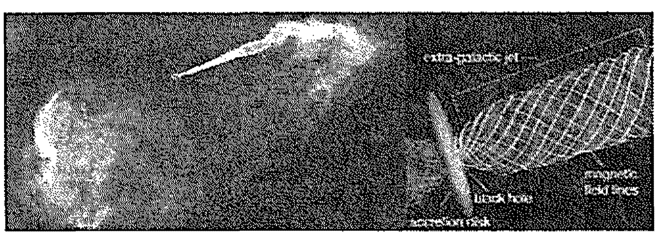
Oral Session 2B

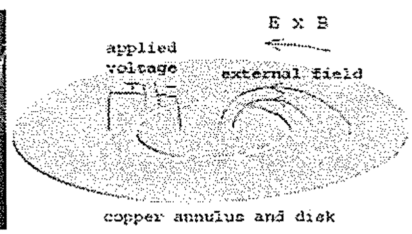
Astrophysical magnetic helicity injection: jets, lobes, and LAPD-U

Xianzhu Tang and Scott Hsu

Los Alamos National Laboratory, Los Alamos, NM 87545

Two spectacular astronomical observations inspire a number of basic plasmas physics problems that have laboratory relevance. The first is the ubiquity of 10^{8-9} solar-mass super-massive black holes at the center of galaxies[1] and on the order of 10^{62} ergs of gravitational energy released *via* accretion. The second is the existence of an almost equally large amount of magnetic energy ($\sim 10^{61}$ ergs) in galactic jet radio lobes[2](see figure left). The physical process by which the accretion disk drives the jet/lobe is thought to be magnetic helicity injection, in which the differential Keplerian disk rotation twists up a magnetic arcade above the disk, directly converting mechanical energy into magnetic energy. In the laboratory, a radial electric field imposed by coaxial electrodes faithfully simulates the same process by drawing current from a power supply to run through a plasma threaded by an externally imposed poloidal magnetic field (see figure right). The toroidal magnetic flux is then injected by the current into the discharge chamber, driving a magnetic bubble expansion. Laboratory electrostatic helicity injection has found usage from spheromak formation[3] to non-inductive current drive in spherical tori[4]. Here we describe the underlying plasma physics for astrophysical jet/lobe that can be addressed by a proposed dedicated experiment on LAPD-U at UCLA.[5] These include theoretical/computational considerations of (1) why jets form? the collimation mechanism for an under- and over-pressured jet; (2) jet stability limit; (3) jet magnetic energy and helicity content, and the *curse of the spheromak*; (4) jet $P\,dV$ work, cosmic shoveling, and angular momentum transfer from the accretion disk by electromagnetic torque. The experimental plan will also be explained, along with the justification of its astrophysical relevance. Useful discussions with H. Li, S. Colgate, R. Lovelace on jet/lobe, A. Boozer on helicity injection, R. Raman and S. Woodruff on laboratory experiments, are gratefully acknowledged. This work was supported by LANL LDRD program.





[1] D. Richstone et al., Nature **395**, A14 (1998).

[2] T. E. Clarke et al., Astrophys. J. **547**, L111 (2001); P.P. Kronberg, Q. Dufton, H. Li, S. Colgate, *ibid* **560**, 178 (2001).

[3] S. C. Hsu and P. M. Bellan, Phys. Rev. Lett. 90, 215002 (2003); J. M. Finn, C. R. Sovinec, D. del-Castillo-Negrete, *ibid* **85**, p.4538-41 (2000)

[4] R. Raman, et al, Phys. Rev. Lett. **90**, p.075005/1-4 (2003); X. Z. Tang and A. H. Boozer, Phys. Plasmas **10**, 3661 (2003); **11**, 171 (2004); to appear in *special issue* (2004).

[5] S. C. Hsu and X. Z. Tang, "A research white paper for LAPD-U: underlying plasma physics of astrophysical jet collimation", LANL report LA-UR-04-0764 (2004).

Tuesday morning, April 27

10:00 to 12:00

Lewis & Clark Room

Poster Session 2C

2C01

Analysis of the Resistive Wall Mode Experiments in HBT-EP

Dmitry Maslovsky, Allen Boozer, Michael Shilov
Department of Applied Physics and Applied Mathematics
Columbia University, New York, NY 10027

A single mode approximation to the exact linear theory is used to study the plasma response as an external magnetic perturbation is applied in the HBT-EP tokamak in the presence of a resistive wall and plasma rotation. The free energy of the least stable plasma mode, given by the dimensionless parameter s, and the torque on the plasma, given by the dimensionless parameter α, completely describe the dynamics of the system near marginal stability. We identify the range of values of s and α corresponding to various dynamical regimes observed in the experiment.

When a resonant static magnetic perturbation is applied in HBT-EP using a set of 30 in-vessel driver coils, the resistive wall mode is excited, and its amplitude and phase are measured with poloidal sensors[1]. The permeability matrix $P = 1/(-s + i\alpha)$ models the plasma response[2]. Here, $s < 0$ corresponds to a stable mode, and $s > 0$ corresponds to an unstable mode without plasma rotation ($\alpha = 0$). The plasma surface inductance, L_p, the resistive wall self-inductance, L_w, and mutual-inductances between the plasma, the resistive wall, and the driving coil, required in the model, are estimated both 1) by using cylindrical geometry approximation, and 2) by matching the ideal wall limit parameter, s_{crit}, to that produced by a VALEN calculation of the growth rate of the RWM for HBT-EP geometry[3]. The plasma stability paramter, s, and the plasma rotation parameter, α, are the only free parameters in the approximation. The cases of the sagging amplitude of the plasma perturbation response are reproduced for $s/s_{crit} \sim 0$ and $\alpha^2/s_{crit}^2 \sim 0.2$, whereas the oscillatory behavior is observed for $s/s_{crit} \sim 0.5$ and $\alpha^2/s_{crit}^2 \sim 0.2$. Non-zero plasma rotation is required in both instances. Further study of the plasma response to an applied external perturbation will include time-dependent $s(t)$ and $\alpha(t)$ parameters.

---

[1] M. Shilov, *et al.*, *Phys. Plasmas*, May, (2004).
[2] A. Boozer, *Phys. Plasmas*, **10**, 5 (2003).
[3] J. Bialek, A. Boozer, M. Mauel, and G. Navratil, *Phys. Plasmas*, **8**, 5 (2001).

2C02

Substorm Energetic Electron Injection Flux from a Dipolarization Model[1]

M. J. Mithaiwala and W. Horton

Institute for Fusion Studies, University of Texas at Austin
Austin, TX 78712

Abstract

During quiet conditions energetic electrons are found in two spatially confined regions around the earth. The inner region is very stable but the outer region which overlaps geosynchronous orbit shows large variation during active periods. The variability of these high energy electrons is then of great interest due to the significance of the geosynchronous region. It is shown that the phase space density of the plasma sheet, a region of of plasma on magnetic field lines farther than $9R_E$ from the Earth, is sufficient to supply the high energy radiation belt electrons. Substorm dipolarizations are a mechanism by which the plasma sheet electrons can be transported to geosynchronous orbit. Further energization of these transported electrons by other mechanisms, such as whistler-wave electron interactions could well account for the dangerous high energy electrons. We estimate using the ten parameter dipolarization model of *Li et al.* [1], a reasonable flux of electrons that can be transported and trapped in the geosynchronous region. The major results of substorm dipolarizations using the *Li et al.* model are reviewed and the effect of parameter variations of the model are given.

[1] Xinlin Li, D. N. Baker, M. Temerin, G. D. Reeves, R. D. Belian. Simulation of dispersionless injections and drift echoes of energetic electrons associated with substorms. GRL **25**, 20, 3763-3766.

[1]This work supported in part by NSF Grant No. ATM-0229863.

2C03

Kinetic Stability Analysis and Collisionless Damping of Zonal Flows*

Liu Chen[1] and Fulvio Zonca[2]
[1]Department of Physics and Astronomy, University of California, Irvine CA 92697-4575, U.S.A.
[2]Associazione EURATOM-ENEA sulla Fusione, C.P. 65 – 00044 Frascati, Italy

Abstract

The crucial role played by zonal flows in regulating the saturation level of drift wave turbulence and ultimately of turbulent transport (see, e.g., Ref. [1]), has brought significant attention on determining the amount of zonal flow which can be spontaneously generated by the turbulence itself before zonal flows become unstable as well due to Kelvin Helmholtz (KH)–like mode excitations [2, 3]. In this framework, drift waves are the "primary" instability and spontaneously generate zonal flows, the "secondary", which can be limited in amplitude by the onset of "tertiary" KH–like modes [2, 3]. The "tertiary" instability has been proposed as explanation for the nonlinear upshift of the critical Ion Temperature Gradient (ITG) driven turbulence threshold [4].

In the present work, we present a kinetic stability analysis of the "tertiary" KH–like modes and determine the threshold condition for their excitation, i.e. the maximum allowable level of zonal flows spontaneously generated by drift wave turbulence. In other words, our work represents extensions of previous studies [2, 3], which are limited to fluid descriptions of the "tertiary" modes and therefore valid in the strongly unstable domain. In the present theoretical framework, we argue that the long lived saturated zonal flow structures, spontaneously generated in ITG turbulence [5, 6], can be considered as generators of *neighboring nonlinear equilibria*, whose stability we analyze with respect to low frequency drift waves with $|k_\perp| \gg |k_z|$, $2\pi/|k_\perp|$ and $2\pi/|k_z|$ being, respectively, drift wave and zonal flow wavelengths.

In toroidal geometry, we demonstrate the crucial role played by trapped as well as barely circulating particles in setting the "tertiary" instability threshold, due to the fact that the characteristic frequency of the KH–like modes is smaller than the typical thermal ion bounce frequency. Starting from the nonlinear gyrokinetic equation [7], we derive the quasineutrality condition for low frequency, long wavelength drift waves in the form of an integral equation [3], whose solution in the local limit gives us a simple estimate for the threshold condition of the "tertiary" instability. Considerations of anomalous collisionless "viscous" damping of the zonal flows via the "tertiary" instability will also be presented.

References

[1] Z. Lin, *et al.*, Science **281**, 1835, (1998).
[2] B.N. Rogers, W. Dorland and M. Kotschenreuther, Phys. Rev. Lett. **85**, 5336, (2000).
[3] F.L. Hinton and M.N. Rosenbluth, Bull. Am. Phys. Soc. **45**, No. 7, 195, (2000).
[4] A.M. Dimits, *et al.*, Phys. Plasmas **7**, 969, (2000).
[5] Liu Chen, Zhihong Lin and Roscoe B. White, Phys. Plasmas **7**, 3129, (2000).
[6] Liu Chen, Roscoe B. White and F. Zonca, Phys. Rev. Lett. **92**, 075004, (2004).
[7] E. Frieman and L. Chen, Phys. Fluids **25**, 502, (1982).

*Work supported by U.S. DOE Grant DE-FG03-93ER54271 and NSF Grant ATM-9971529

2C04

Semi-implicit Treatment of the Hall Term in NIMROD*

H. Tian and C. R. Sovinec

Center for Plasma Theory and Computation, University of Wisconsin
Madison, WI 53706

Abstract

For nonlinear macroscopic behavior in magnetically confined plasmas, the two-fluid model has a range of time-scales that is at least $k\delta_i$ larger than in the resistive MHD model, where δ_i is the ion skin depth and k is the largest relevant wavenumber. Since the MHD system is stiff and important two-fluid effects occur at spatial scales that are smaller than the ion skin depth, modeling two-fluid behavior with numerical simulation is quite challenging. Fortunately, the macroscopic behavior does not depend on how force-balance is achieved in the electron momentum equation, so time-steps need not be limited to whistler and kinetic Alfven wave propagation times. Nonetheless, the solution at every step must respect the electron force balance at the spatial scales of the nonlinear macroscopic dynamics. With the relatively small magnetic perturbations encountered in fusion plasmas, the dominant part of the stiffness is related to linear behavior, even in nonlinear conditions. Thus, the semi-implicit method has proven effective for solving the nonlinear MHD system [1], and a similar approach has been applied to address the Hall term in an extended-MHD description [2]. Here, we describe modifications to the algorithm presented in Ref. [2] that make it suitable for a high-order finite element spatial representation with C^0 continuity [3]. The symmetric fourth-order differential operator used to stabilize the numerical advance is implemented through an auxiliary vector field, so that all terms in the weak form of the magnetic advance are integrable for the space of C^0 piecewise polynomials. The resulting algebraic system is nonsymmetric, but in the NIMROD implementation [http://nimrodteam.org], we have found the SuperLU sparse parallel linear solver library [http://crd.lbl.gov/~xiaoye/SuperLU/] to be very effective for solving the resulting matrices. The numerical algorithm and NIMROD implementation are tested on computations of simple whistler waves in a doubly periodic domain and in bounded domains. Results computed with the fourth-order semi-implicit operator are compared with numerical dispersion relations and with results from a simpler algorithm using a second-order differential operator. Initial applications to inhomogeneous equilibria are also presented.

*This work is supported by the U.S. Department of Energy.

[1]D.D. Schnack, D.C. Barnes, Z. Mikic, et al., J. Comput. Phys. 70, 330 (1987)
[2]D.S. Harned and Z. Mikic, J. Comput. Phys. 83, 1 (1989)
[3]C.R. Sovinec, *et al.*, "Nonlinear magnetohydrodynamics simulation using high-order finite elements," J. Comput. Phys., in press.

2C05

Further investigations of electromagnetic gyrokinetic simulation of plasma turbulence

David W. Ross[1] and William Dorland[2]

[1]IFS and FRC, The University of Texas at Austin, Austin, TX 78712-0262
[2]The University of Maryland, College Park, MD 20742-3511

In previous gyrokinetic simulations of tokamak plasma turbulence with the electromagnetic nonlinear code GS2, we found an enhancement of the electron thermal flux owing to the magnetic fluctuations.[1,2] This effect is reduced, however, at high spatial resolution.[2] In the present work we extend the study to even higher resolution, retaining 14 Fourier modes poloidally and 99 in the radial direction. The computational flux-tube size is 112 ion gyro-radii poloidally and 72 radially. The runs appear to be approaching convergence but have still not converged completely, the energy fluxes being somewhat reduced from our previous highest-resolution case. The necessary radial resolution results from the presence of drift-Alfvén waves that are extended along the field line in this system with magnetic shear. These modes are linearly unstable. The most interesting result is that the presence of the Alfvén modes appears nonlinearly to suppress the ion thermal flux, which is substantially below that of the corresponding electrostatic run, even at the low value of □ = 0.003. This could have a bearing on previous attempts to compare with experiment using electrostatic runs.[3]

[1]D. W. Ross, W. Dorland, and B. N. Rogers, Bull. Am. Phys. Soc. 46, 115 (2001).
[2]D. W. Ross and W. Dorland, presented at the Transport Task Force Meeting, Madison, WI April 2-5, 2003. See http://www.psfc.mit.edu/ttf/2003/previews/agenda.html
[3]D. W. Ross and W. Dorland, Phys. Plasmas 9, 5031 (2002).
Presented at the 2004 International Sherwood Theory Conference, April 26-28, Missoula, MT

2C06

Granulation Formation and Turbulent Trapping in Wave Kinetics

P.H. Diamond,[1] K. Itoh,[2] S.-I. Itoh,[3] T.S. Hahm[4]

[1] University of California, San Diego, La Jolla, CA 92093-0319 USA
[2] National Institute for Fusion Studies, Toki, Gifu-Ken 509-5292 Japan
[3] Research Institute for Applied Mechanics, Kyushu University, Kasuga-City, Fukuoka 816 8580 Japan
[4] Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451 USA

Plasma physics has contributed two notable problems to nonlinear science, namely the problem of Vlasov turbulence and the nonlinear modulation instability or "collapse" problem, typified by the Langmuir turbulence problem. Here, we combine the ideas and methods of these two problems to describe turbulent trapping in nonlinear modulational dynamics.

We argue that it is convenient to classify approaches to the well-known modulation dynamics problems according to their location in a 2D space parametrized by the eikonal ray Chirikov parameters (which exceeds unity when group-phase resonances overlap) and the ray Kubo number K (which exceeds unity when a trapped ray bounces several times in a single structure). The regime where $s > 1$ and $K \gtrsim 1$ is the regime of *turbulent trapping*. We show that both the 1D Langmuir and 2D drift wave-zonal flow interaction problems in this regime may be mapped to the 1D Vlasov turbulence problem in the regime of turbulent trapping. We then apply the theory of phase space density granulation, developed for turbulent trapping in Vlasov systems, to describe the turbulent trapping of waves in modulation structures. We focus on three specific issues, namely:

i.) the modification of the dynamics of relaxation of the wave population $\langle N \rangle$ induced by granulations. In particular, the diffusive quasi-linear wave-kinetic equation is replaced by a Lenard-Balescu type equation, with a drag, induced by incoherent fluctuations in N (i.e. granulations).

ii.) the appearance of novel modulational instability mechanisms related to granulations.

iii.) the role and significance of caustics in the theory. These are interesting as they have *no* counterpart in the Vlasov turbulence problem.

Special attention will be given to turbulent trapping in drift wave-zonal flow turbulence.

2C07

Stabilization of Line Tied Resistive Wall Kink Modes Using Rotating Walls*

C. C. Hegna and C. B. Forest
Dept. of Engineering Physics, University of Wisconsin
Madison, WI 53706-1687

Abstract

A method for stabilizing the resistive wall mode (RWM) in a line tied screw pinch equilibrium is investigated. Following the original suggestion of Gimblett [1], two differentially rotating, radially separated walls are included in the analysis. If both walls are inside the critical radius for stabilization of the external ideal kink mode and the walls are separated, sufficiently large rotation of the wall is capable of stabilizing the RWM.

What distinguishes this work from prior investigations [2] is the effect of line tied boundary conditions. This axial boundary condition provides a substantial stabilizing effect [3]. Unlike the case of a periodic cylinder, where the linear response of magnetic perturbations can be represented by a single Fourier harmonic, $\tilde{\mathbf{B}} \sim e^{im\theta - in\zeta}$, line tied boundary conditions require that the eigenmode satisfy a partial differential equation. In the periodic cylinder case, the ideal kink becomes very unstable when the edge q value lies just below a low order rational. In this case, it is very difficult to stabilize the configuration with differentially rotating walls. For the case of line tied boundary conditions, instability is only present when the edge q drops below unity. Differentially rotating walls allow access to the $q_a < 1$ regime with the stability region growing with increasing differential rotation. As in the periodic cylinder case, for a given equilibrium, there is an optimal placement of the second rotating wall relative to the first wall.

References

[1] C. G. Gimblett, Plasmas Phys. Controlled Fusion **31**, 2138 (1989).
[2] C. C. Hegna and C. B. Forest, "Stabilization of Resistive Walls Modes with Rotating Walls," UW-CPTC Report 00-03 (2000).
[3] D. D. Ryutov, R. H. Cohen, and L. D. Pearlstein, Bull. Am. Phys. Soc. **48**, 167 (2003).

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

New Results on the Theory Anomalous Transport Reduction by shearing: Mean shear and zonal shears

Eun-jin Kim and P.H. Diamond

University of California, San Diego, La Jolla, CA 92093-0319 USA

Abstract

The reduction of turbulent transport by shearing is critical for the transition to H-mode and for the formation of internal transport barrier. While recent experiments indicate rather strong suppression of heat and particle transport $\propto \Omega^{-\alpha}$ $(1.6 < \alpha < 4.8)$ [1], the understanding and theoretical prediction of this scaling is still lacking.

We report the reduction in the transport of particle and heat by a strong mean shear flow in the interchange and ion-temperature gradient turbulence models. Compared to the passive scalar transport [2], a stronger reduction in the transport (down to $\Omega^{-3} \ln \Omega$) results from a severe reduction in the amplitude of turbulent velocity in both models. However, the cross-phase is only modestly reduced, similar to the scalar field case [2], and contrary to recent claims in the literature [3]. These results highlight the importance of the property of the flow in determining the overall transport level.

We also assess the efficiency of *random shearing* by *zonal flows* in transport reduction in a scalar field model. In the strong shear limit, the flux is found to have a similar scaling with the RMS shear Ω_{rms} as $\propto \Omega_{rms}^{-1}$, compared to the case of a coherent shearing. A random zonal flow with a finite correlation time τ_{ZF} renders decorrelation of two nearby fluid elements less efficient, with its time $\tau_D = (\tau_\eta / \tau_{ZF} \Omega_{rms}^2)^{1/2}$ (τ_η is turbulent scattering (diffusion) time), leading to larger amplitude with a slightly different scaling ($\propto \tau_D/\Omega_{rms}$). If $\tau_{ZF} \gg \tau_D$, results recover those for steady linear shear flow. Thus, the effectiveness of zonal shear decorrelation depends on *both* the strength of the shear *and* its auto-correlation time.

[1] J. Boedo, *et al*, Phys. Rev. Lett. **84**, 2630 (2000).

[2] E. Kim and P.H. Diamond, Phys. Rev. Lett. **91**, 075001 (2003).

[3] P.W. Terry, *et al*, Phys. Rev. Lett. **87**, 185001 (2001).

2C09

Singularities and bifurcations in models for L–H transitions

R. Ball
e-mail Rowena.Ball@anu.edu.au
Department of Theoretical Physics, Australian National University
Canberra 0200 Australia

In this presentation I introduce some investigations of the structural properties of low-order models for plasma dynamical behavior using bifurcation and and stability analyses, and show how this approach can provide a guide for experimental design.

During the last decade efforts to model plasma mass dynamics around L–H transitions and concomitant oscillatory phenomena have concentrated on low-order or low-dimensional models. What drives this approach is the predictive power that a unified, low-order description of the bulk dynamics would have in designing and controlling confinement states. For example, a model that speaks of the shape and extent of hysteresis in the L–H transition would be an invaluable tool for economical management of confinement: given the number of parameters that *could* be varied around a hysteretic régime, it would be cheaper—i.e.. save hundreds of cpu hours and/or expensive diagnostics—to know in advance which ones actually *do* affect the hysteresis, and which do not.

Low-order models are powerful because they are supported by well-developed theories and methodologies that give qualitative and global insight, such as bifurcation, stability, and symmetry theory. However, there are some rocky shores in the quest for a low-dimensional sub-space that captures the generic dynamics of L–H transitions [1, 2]. The heart of the matter is the relationship between the bifurcation structure of a dynamical model and the physics of the process it is supposed to represent. If we probe the nature of this relationship we find that degenerate singularities ought to reflect some matching physics—the point of onset of hysteresis, for example, or a fragile symmetry—or they are pathological. In the one case we can usually unfold the singularity in a physically meaningful way; in the other case we know that something is wrong and we can scrutinize our assumptions carefully. In both cases we have learned richly. Degenerate singularities provide opportunities to improve a model and its predictive capabilities.

Here I apply this approach to two models. The first is a model for L–H transitions [3], extended to include poloidal flow generation by ion orbit losses [4, 5]. As this rate is tuned the system passes from a hysteretic régime where stable shear flows draw energy from the turbulence via Reynolds stress decorrelation, to a qualitatively different hysteretic domain dominated by the radial electric field. The smooth path between these two extremes passes through an intermediate domain where transitions are oscillatory and hysteresis is locally forbidden. These results provide unification of previous disparate models for L–H transitions, and also suggest control and optimization strategies.

The second model highlights the role of the interaction between zonal flows and mean shear flows in the transfer of energy from the pressure gradient to the turbulence and generation of zonal flows [6]. A bifurcation analysis confirms the prediction that mean shear flow can inhibit zonal flow growth, and smooth unfoldings of degenerate singularities elicit the predictive possibilities in the model.

[1] R. Ball and R. L. Dewar. *Phys. Rev. Lett.*, 84(14):3077–3080, 2000.
[2] R. Ball and R. L. Dewar. *J. Plasma Fus. Res.*, 4:266–270, 2001.
[3] R. Ball, R. L. Dewar, and H. Sugama. *Phys. Rev. E*, 66:066408–1–066408–9, 2002.
[4] S.-I. Itoh and K. Itoh. *Phys. Rev. Lett.*, 60(22):2276–2279, 1988.
[5] K.C. Shaing and E.C. Crume. *Phys. Rev. Lett.*, 63(21):2369–2372, 1989.
[6] E-J. Kim and P. H. Diamond. *Phys. Rev. Lett.*, 90(18):185006–1–185006–4, 2003.

2C10

Collisional effects in gyrokinetic particle simulation

Thomas G. Jenkins and W. W. Lee

Princeton Plasma Physics Laboratory, Princeton, NJ 08543*

An electrostatic split-weight gyrokinetic particle simulation scheme [1] in two-dimensional shearless slab geometry is used to study the effect of electron-ion collisions (pitch-angle scattering) on drift instabilities and steady-state transport. Previously published results [2] indicate that the nonlinear saturation amplitude of drift modes can be greatly enhanced by (relatively weak) collisional effects, with the dominant physical mechanism underlying the saturation of the modes being the $\mathbf{E} \times \mathbf{B}$ nonlinearity. We show that this behavior can be simulated in the gyrokinetic split-weight formalism, and that one-dimensional modes (whose saturation levels are determined by the parallel velocity nonlinearity [3]) also exhibit enhanced growth rates and saturation levels in the presence of collisions. Some effects of collisions on the steady-state transport properties of the plasma are also presented, including an exploration of the balance between particle flux, collisional dissipation, and entropy production.

* Work supported by U. S. DoE and the SciDAC project.

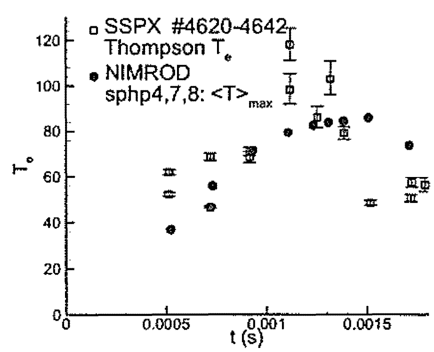
[1] I. Manuilskiy and W. W. Lee, Phys. Plasmas **7**, 1381 (2000).
[2] J. F. Federici, W. W. Lee, and W. M. Tang, Phys. Fluids **30**, 425 (1987).
[3] S. E. Parker and W. W. Lee, Phys. Fluids B **5**, 77 (1993).

Integrated Modeling of Spheromak MHD and Energy Transport*

C. R. Sovinec[1], G. A. Cone[1], and B. I. Cohen[2]
[1]Center for Plasma Theory and Computation, University of Wisconsin
Madison, WI 53706
[2]Lawrence Livermore National Laboratory
Livermore, CA 94550

Abstract

Through numerical simulation, we have previously shown that the zero-beta MHD model reproduces the most important magnetic characteristics of electrostatically driven spheromaks, including poloidal flux amplification, n=1 activity during formation, periodic relaxation events in some conditions, and closed flux-surface formation during decay [1]. While these numerical results are at least qualitatively consistent with many spheromak experiments, the energy confinement properties [2] of the predicted magnetic topology in sustained conditions [3] cannot account for peak observed temperatures [4]. Recent computations include temperature evolution that is consistent with the simulated evolving magnetic topology, using thermal transport coefficients, electrical resistivity, and Ohmic heating appropriate for collisional plasmas. The temperature dependencies of the coefficients produce striking effects in the simulated spheromak evolution. The cold edge plasma tends to impede parallel thermal conduction to the wall in the driven conditions with chaotic magnetic topology, allowing the plasma core temperature to reach tens of eVs, as expected [2]. However, when the drive is temporarily removed, the cold edge plasma assists magnetic reconnection, so that large closed flux surfaces form rapidly, and core temperatures increase to approximately 100 eV. Applying a second current pulse, as in some SSPX discharges [4], is shown to improve performance by delaying the onset of MHD modes that are resonant in the closed-flux region. A detailed comparison of results from nonlinear simulations with laboratory measurements from SSPX confirms the effectiveness of the integrated MHD/energy transport modeling for this application.



Comparison of integrated MHD/energy transport simulation results with measured temperatures in the SSPX spheromak. [SSPX data courtesy of H. S. McLean.]

*This work is supported by the U.S. Department of Energy.

[1]C. R. Sovinec, J. M. Finn, D. del-Castillo-Negrete, Phys. Plasmas 8, 475 (2001).
[2]R. W. Moses, R. A Gerwin, K. F. Schoenberg, Phys. Plasmas 8, 4839 (2001).
[3]J. M. Finn, C. R. Sovinec, and D. del-Castillo-Negrete, Phys. Rev. Lett. 85, 4538 (2000).
[4]H. S. McLean, *et al.*, Phys. Rev. Lett. 88, 125004, (2002).

2C12

Lyapunov stability of certain MHD systems

H. Tasso*, G. N. Throumoulopoulos†
* Max-Planck-Institut für Plasmaphysik, Euratom Association, D-85787 Garching, Germany
† University of Ioannina, Association Euratom - Hellenic Republic. Section of Theoretical Physics, GR 451 40 Ioannina, Greece

Abstract

The present study consists of two parts. The first one [1] relates to a previous publication [2] in which dissipative magnetized Trkal flows were proved to be Lyapunov stable nonlinearly under the conditions of sufficiently small Reynolds number and of an upper bound of the "force-free" current. An alternative Lyapunov functional containing the cross helicity and introduced recently for conservative magnetized Beltrami flows [3] is extended here to the Trkal flows mentioned above. Stability is now proved under limitations on maximal velocity and current without introducing an upper bound on the Reynolds number. In the second part [4] a previous theorem by Pfirsch and Tasso [5] concerning "resistive wall modes" is extended in a "weak sense" to the case of time-dependent wall resistivity. Instability growth behaviour remains, however, an open problem.

[1] H. Tasso, G. N. Throumoulopoulos, Phys. Plasmas **10**, 4897 (2003).
[2] H. Tasso, Phys. Plasmas **2**, 1789 (1995).
[3] Z. Yoshida, S. Ohsaki, A. Ito, S. M. Mahajan, J. Math. Phys. 44, 2168 (2003).
[4] H. Tasso, G. N. Throumoulopoulos, Phys. Plasmas **11**, 334 (2004).
[5] D. Pfirsch, H. Tasso, Nuclear Fusion **11**, 259 (1971).

Particle-in-Cell Simulations of ICRF Wave-Particle Interaction

Johan Carlsson

Tech-X Corporation, 5621 Arapahoe Avenue, Boulder, CO 80303

Abstract

When nonlinear effects come into play, traditional, linear RF theory becomes invalid. An example of when this can occur is during coupling of ICRF waves (e.g. IBWs). Because of the low densities and temperatures at the plasma edge, the wave energy density in front of an antenna can greatly exceed the plasma energy density. In this region, ponderomotive and other nonlinear effects can significantly affect the antenna-plasma coupling.

The Particle-in-Cell (PIC) algorithm [1] directly solves the coupled set of Maxwell's equations and the equations of motion for a distribution of macroparticles (representing the real particles). Because few approximations are made the relevant nonlinear physics is retained and reproduced by PIC simulations. The directness of the PIC approach does however make it computationally demanding; small timesteps and many macroparticles are necessary for converging the solution.

To make PIC simulations (of coupling or other phenomena) over many ion gyroperiods feasible, it is necessary to use algorithms that remove the fastest, physically uninteresting timescales. We have modified the PIC code VORPAL [2] so that the timestep is no longer limited by neither the Courant condition nor the electron gyroperiod.

The removal of the Courant condition was achieved by implementing the implicit field solver of Bowers [3]. The Bowers scheme uses modified versions of Faraday's and Ampere's laws where damping is directly included in the curl terms. Bowers shows that after Crank-Nicholson time discretization the level of damping corresponds directly to the degree of implicitness. I.e., as the damping parameter is increased, the discretized equations go from fully explicit to fully implicit.

The electron gyroperiod is three orders of magnitude shorter than the timescale of interest: the ion gyroperiod. By replacing the electron equation of motion with its gyrocenter counterpart, the physically uninteresting electron gyration is removed while the physically important electron Landau damping is kept.

We have also implemented a simple antenna model in VORPAL to allow us to perform coupling simulations.

We will describe the algorithms we have used to remove the fastest timescales and to make VORPAL a tool for direct simulations of ICRF wave-particle interaction. Preliminary results will be presented.

[1] C. K. Birdsall and A. B. Langdon, *Plasma Physics via Computer Simulation*, (IoP Publishing, Bristol, 1991).

[2] C. Nieter and John R. Cary, "VORPAL: a versatile plasma simulation code", to be published in J. Comp. Phys.

[3] K. J. Bowers, "Implicit methods of solving the Maxwell equations suitable for particle-in-cell simulation of low temperature plasmas", submitted to J. Comp. Phys.

2C14

Impact of field line label and ballooning parameter on infinite-*n* ballooning stability in compact stellarators

D. Westerly,[1] A. S. Ware,[1] R. Sanchez,[2] L. A. Berry,[3] G. Y. Fu,[4] S. P. Hirshman,[3]
J. F. Lyon,[3] D. A. Spong,[3] D. J. Strickler[3]

[1]*University of Montana-Missoula, Missoula, Montana 59812*
[2]*Universidad Carlos III de Madrid, Madrid, Spain*
[3]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*
[4]*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543*

The infinite-*n* ideal ballooning mode stability of a non-axisymmetric equilibrium is a function of the ballooning parameter, $\square_k = k_r/k_{\square}$ and the field line label, $\square = \square \square \square \square$. Here, k_r and $k_{\square}$ are the components of the wavenumber perpendicular to the magnetic field and $\square$ is the rotational transform. In this work, the impact of field line label and ballooning parameter on the infinite-*n* ballooning stability of compact, quasi-poloidal symmetric stellarators is investigated. Previously, the ballooning stability of quasi-poloidal stellarators has been examined for fixed-boundary, very-high $\square$ ($\square$ >10%), tokamak-stellarator hybrid configurations [1] and free-boundary, moderate $\square$ ($\square$>4%) plasmas in the Quasi-Poloidal Stellarator (QPS) [2]. These previous calculations were performed with $\square_k$, $\square = 0$. Here, these results are extended to include other possible values of $\square_k$ and $\square$. The first ballooning instability $\square$-limits for these devices are well described by the $\square_k$, $\square$ = 0 results. Changing either $\square_k$ or $\square$ increases the $\square$ required for first instability. The $\square$ values required to enter second ballooning stability are higher when $\square_k$, $\square \square$ 0. The plasma is still first-unstable to modes with $\square_k$, $\square \square 0$ even after modes with $\square_k$, $\square = 0$ (and regions nearby in parameter space) become second stable. These results are compared with calculations of the stability of finite-*n* ballooning modes in both the hybrid configuration and the QPS configuration.

[1] A. S. Ware, S. P. Hirshman, D. A. Spong, et al., Phys. Rev. Lett. **89**, 125003 (2002).
[2] A. S. Ware, D. Westerly, E. Barcikowski, et al., "Second ballooning stability in high-$\square$, compact stellarators", to appear in Phys. Plasmas (2004).

2C15

Single Helicity and Quasi-Single Helicity States in Reversed Field Pinches

J. M. Finn, R. A. Nebel, C. G. Bathke

Los alamos National Laboratory
Los Alamos, New Mexico 87545

Abstract

Previous studies have shown that both single helicity[1] (SH) and quasi-single helicity[2] (QSH) states can emerge from 3-D RFP dynamics. However, both states have previously been observed to exist only at very low Hartmann number H and thus have been of limited relevance to present-day and future experimental devices. There is hysteresis between the QSH states and the multiple helicity state (MH) as H is changed. This hysteresis is deepened, in particular QSH states can exist for larger H, if there is an applied radial magnetic field on the wall (a field error). We have found that QSH states can also be achieved at high H if another form of external helical perturbation, of an electrostatic nature, is applied to the dominant helical mode. These perturbations are applied in a manner such that the radial magnetic field vanishes at the boundary so no flux surfaces intersect the wall.

Using this technique, QSH RFP states at higher H have been achieved when a toroidal loop voltage is applied. The observed QSH sidebands are ~ 4 toroidal mode numbers away from the dominant mode. The dominant mode appears to flattens the current profile local to the dominant resonance, which stabilizes the adjacent modes.

When the toroidal loop voltage is removed, preliminary studies indicate that it is possible for the plasma to go into a QSH state of quite narrow spectrum. These studies suggest that the applied helical electrostatic field can drive both net toroidal current and poloidal current, and a large region of good flux surfaces can exist, but toroidal field reversal is lost. Further studies of these states will be shown.

1. J. M. Finn, R. A. Nebel, C. G. Bathke, *Phys. Fluids B* **4**, 1262 (1992).

2. S. Cappello, D. F. Escande, *Physical Review Letters* **85**, 3838 (2000).

Mode Conversion Processes to attain Electron Cyclotron Emission in Spherical Tokamaks

J. Preinhaelter[1], V. Shevchenko[2], M. Valovic[2],H. R. Wilson[2], P. Pavlo[1], L. Vahala[3], G. Vahala[4], J. Urban[1]
[1]EURATOM/IPP.CR Association, Institute of Plasma Physics, , 182 21 Prague, Czech Republic
[2]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, , OX14 3DB UK
[3]Old Dominion University, Norfolk, VA 23529
[4]College of William & Mary, Williamsburg, VA 23185

Abstract

Spherical tokamaks are characterized by low magnetic fields and high plasma density. Under these conditions, cutoffs prevent the radiation of O- and X- modes from the first 5 electron cyclotron harmonics from reaching the plasma boundary. Thus any ECE radiation that is detected outside the plasma must arise from electron Bernstein waves (EBW) generated near the plasma center. While these electrostatic EBW cannot be detected in a vacuum, they undergo mode conversion to electromagnetic waves in the upper hybrid region and these electromagnetic waves can be detected. Detailed 3D modeling of the MAST plasma includes the effects of bootstrap, diamagnetic and Pfirsch-Schluter currents on the magnetic surfaces. This yields better fit to experimental ECE data than earlier attempts which assumed very simple current profile and ignored many details of the physics of the H-mode. The plasma density and temperature profiles are obtained from high spatial resolution Thomson scattering measurements while the measured Z_{eff} is incorporated into the simulation code. The effect of collisions on the absorption of EBW and the weakening of the ECE is examined.

Our ECE simulation codes also use a more sophisticated representation of the ECE antenna (on considering the reciprocal process of the launch electromagnetic waves into the plasma, with these waves mode converting finally to the EBW which is then absorbed near an electron cyclotron harmonic.). This model incorporates the horn, a thin lens, two mirrors and a window. With the Gaussian beam formalism the exact positions of the waists and the corresponding angular beam divergence at each frequency can be determined. Ray tracing is used to determine the intensity of EBW, and for each ray the EBW-X-O mode conversion efficiency is calculated at the UHR within the transport barrier. An adaptive finite element code has been developed to study the full wave problem.

The interaction of neoclassical and turbulent transport in toroidal systems

H.E. Mynick[1], A.H. Boozer[2]

[1]Princeton Plasma Physics Laboratory, Princeton, NJ

[2]Dept. of Applied Physics & Mathematics, Columbia University, New York, NY

We study the interaction of neoclassical and turbulent transport in tokamaks and stellarators. The theory of neoclassical transport in these devices is well developed, and a large amount of work has also been done on turbulent transport, mainly in tokamaks or simpler systems. We consider how the transport changes when one superposes on the background fields producing the neoclassical transport a spectrum of (possibly time-dependent) electrostic modes ϕ_k representing turbulence. A simple guess, commonly assumed, is that the effects are approximately additive, with total diffusion coefficient $D = D_0^{nc} + D^{an}$ being the sum of neoclassical and anomalous contributions, *e.g.*, with D^{an} having a linear dependence $D^{an} \simeq D_1|\phi|$ characteristic of strong turbulence, or a quadratic dependence $D^{an} \simeq D_2|\phi^2|$ characteristic of weak turbulence, quasilinear theory, and some ripple transport regimes, increasing with larger ϕ. Instead, one might expect the turbulence to enhance the total effective collisionality $\nu_{ef} = \nu_0 + \nu_{an}$ over the purely collisional rate ν_0, shortening the decorrelation time. For axisymmetric systems, such an effect would again increase D over D_0^{nc}. However, stellarators and rippled tokamaks have collisionality regimes where $D \sim 1/\nu$, so for these, an enhanced ν_{ef} would *decrease* D, of possible significance for finding an optimal stellarator design or operating point. Using a guiding-center code as our primary tool for exploration, we investigate under what circumstances these two intuitions, and others, prove valid.

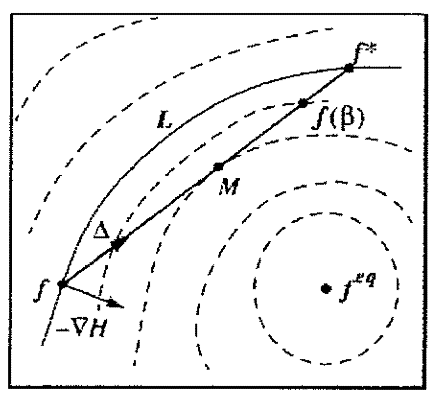
Entropic Lattice Boltzmann Schemes

G. Vahala[1], L. Vahala[2]
[1]College of William & Mary, Williamsburg, VA 23185
[2]Old Dominion University, Norfolk, VA 23529

Abstract

The straightforward Lattice Boltzmann scheme to solve nonlinear macroscopic equations like MHD is a very powerful, highly parallelizeable simple algorithm that has attained 3.6 Tflops/s on the *Earth Simulator*[1]. However, more refined schemes must be developed to avoid nonlinear numerical instabilities – especially as one pushes to regimes of smaller transport coefficients. The instabilities typically manifest themselves by the distribution function going negative in some regions of phase space. Recently[2], an elegant formulation of LBM has been introduced which ensures nonlinear numerical stability and the realizability constraint of non-negative distribution functions at every time step through the introduction of a discrete Liapunov functional. There are 4 basic steps : (1) determination of a discrete convex H-function subject to the appropriate moment constraints, (2) the determination of a bare collision operator Δ (not necessarily BGK); (3) the existence of a functional $\alpha[f]$ so that $H[f] = H[f + \alpha\Delta]$; (4) the evolution of the discrete kinetic equation is through the dressed collision operator $\Delta^* = \beta\alpha[f]\Delta$ where β is a parameter that controls the transport coefficient.

This entropic scheme is unconditionally stable. A plot of surfaces of $H = const.$ has an initial f on the surface L, with $-\nabla H$ having a component towards f^{eq}. Bare collision operator Δ drives the system to lower H, with $\alpha[f]$ so that $H[f] = H[f + \alpha\Delta] = H[f^*]$. Thus α is the maximal that will still permit a local H-theorem and realizability. The parameter $0 \le \beta \le 1$ yields the dressed collision operator $f \to (1-\beta)f + \beta f^*$, with $\beta \to 1$ yielding transport coefficients $\to 0$.



We shall employ this entropic lattice Boltzmann approach to the KdV and 1D MHD models.

[1] J. Carter, G. Vahala, L. Vahala, A. Macnab, M. Soe, Parallel CFD2004 (to be published)

[2] S. Ansumali and I. V. Karlin, Phys. Rev. **E62**, 7999 (2000); Phys. Rev. **E65**, 056312 (2002); J. Stat. Phys. **107**, 291 (2002);

Implicit Lattice Boltzmann Schemes

C. Schleif[1], G. Vahala[1], L. Vahala[2], A. I. D. Macnab[3]
[1]College of William & Mary, Williamsburg, VA 23185
[2]Old Dominion University, Norfolk, VA 23529
[3] CSCAMM, University of Maryland, College Park, MD 20742

Abstract

The accurate numerical modeling of the nonlinear convective derivatives in MHD requires sophisticated treatments – as seen in the high finite element NIMROD code[1] or in a Newton-Krylov Jacobian-free algorithm[2]. Lattice Boltzmann schemes, on the otherhand, embed the macroscopic conservation equations into the higher dimensional kinetic space. For appropriate velocity-space lattice symmetries, the Chapman-Enskog limit of the lattice Boltzmann equation will recover the desired nonloinear macroscopic equations. The typical lattice Boltzmann BGK kinetic equation takes the form

$$\frac{\partial f_i}{\partial t} + \mathbf{e}_i.\nabla f_i = -\frac{1}{\tau}\left[f_i - f_i^{eq}\right], \quad i = 1 \ldots b$$

where $\mathbf{e}_i$ is the lattice velocity vector and τ is the relaxation rate at which f_i tends to the 'equilibrium' distribution function f_i^{eq}. The simplicity of the scheme, its replacement of the nonlinear macroscopic convective derivatives by simple linear advection and local algebraic noninearity in the f_i^{eq}, its ideal implementation on multiparallel processors are very attractive features. In particular, timings[3] on the vector *Earth Simulator* machine has resulted in not fully optimized 2D MHD lattice Boltzmann code running at over 3.6 Tflops/s.

These explicit Lattice Boltzmann schemes require small time steps and numerical stability is an issue with the standard polynomial expansion of f_i^{eq} in the macroscopic moments. Here we examine the Cao et. al[4] implicit scheme (which decouples the spatial grid from the velocity lattice)

$$f_i(\mathbf{x},t+\Delta t) = f_i(\mathbf{x},t) - \frac{\Delta t}{\Delta x}\left[f_i(\mathbf{x},t) - f_i(x-\mathbf{e}_i\,\Delta x,t)\right] - \frac{\Delta t}{\varepsilon\tau}\left[f_i(\mathbf{x},t+\Delta t) - f_i^{eq}(\mathbf{x},t+\Delta t)\right]$$

No matrix inversions are required for this implicit scheme since the relaxed distribution function f_i^{eq} at time $t+\Delta t$ is immediately obtained from the moments of this implicit scheme.

An explicit lattice Botlzmann scheme is constructed for the collision of solitons of the KdV equation. These explicit results are compared to those arising from the implicit scheme with tests made on the allowed time steps.

[1] C. R. Sovinec, D. C. Barnes, T. A. Gianakon, A. J. Glasser, R. A. Nebel, S. E. Kruger, D. D. Schnack, S. J. Plimpton, A. Tarditi, M. S. Chu, NIMROD Team, J. Computat. Phys. (to be published)
[2]L. Chacon, D. A. Knoll, J. M. Finn, J. Computat. Phys. **178** 15 (2002)
[3] J. Carter, G. Vahala, L. Vahala, A. Macnab, M. Soe, Parallel CFD2004 (to be published)
[4] N. Cao, S. Chen, S. Jin, D. Martinez, Phys. Rev. **E55**, R21 (1997)

2C20

Finite gyroradius effects on drift compressional modes in very high β plasmas.

Chris Crabtree and Liu Chen
Department of Physics and Astronomy, University of California, Irvine

A dispersion relation for low frequency drift compressional modes in very high β plasmas with finite gyroradius effects, $k_\perp \rho_i \sim O(1)$, is derived from the coupled gyrokinetic-Maxwell equations using two small parameters: 1) cold electrons $T_e/T_i \sim O(\delta)$ (to decouple the electrostatic modes from the compressional modes) and 2) the smallness of the mode localization width along the field line (to decouple the shear Alfvén modes from the compressional modes). In very high beta plasmas, $\beta \sim 0(1)$, such as the earth's magnetosphere, the strength of the magnetic field can be a very strong function of the distance along the field. This strong dependence allows the mode to be extremely localized and thus decoupled from the shear Alfvén mode. The derived dispersion relation is analyzed and solved to demonstrate that drift compressional modes can become unstable when the density gradient and ion temperature gradient are in the opposite directions ($\eta_i < 0$) or when the magnetic guiding center drift is opposite to the ion diamagnetic drift ($\omega_{*i}/\omega_{Di} < 0$). The dependence of the mode growth rate on $k_\perp \rho_i$ is studied in detail. It is found that, in general, the most unstable modes have a finite gyroradius. Effects of finite gyroradius in localizing the radial mode structures will also be discussed. [1]

[1] Chris Crabtree is supported in part by an appointment to the U.S. Department of Energy Fusion Energy Postdoctoral Research Program administered by the Oak Ridge Institute for Science and Education. Liu Chen is supported in part by U.S. Department of Energy and National Science Foundation grants.

2C21

Electron-inertia Effects on Driven Magnetic Field Reconnection

B.K. Shivamoggi and N. Al-Salti
University of Central Florida
Orlando, Florida

Electron-inertia effects on the magnetic field reconnection induced by perturbing the boundaries of a slab of plasma with a magnetic neutral surface inside are considered. Energetics of the tearing-mode dynamics with electron inertia which controls the linearized collisionless MHD are considered with a view to clarify the role of the plasma pressure in this process. Cases with the boundaries perturbed at rates slow or fast compared with the hydromagnetic evolution rate are considered separately. When the boundaries are perturbed at a rate slow compared with the hydromagnetic evolution rate and fast compared with the resistive diffusion rate a current sheet forms at the magnetic neutral surface which then disappears via exponential damping and diffusion and reconnection takes place. On the other hand, when the boundaries are perturbed at a rate fast compared with the hydromagnetic evolution rate, there is no time for the current sheet formation and reconnection to take place.[1]

[1] N. Al-Salti and B. K. Shivamoggi: *Phys. Plasmas* **10**, 4271 (2003).

2C22

Plasma detachment in a magnetic nozzle

A.V. Arefiev and B.N. Breizman

The University of Texas at Austin, Austin, TX 78712

Abstract

This work has been motivated by the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) project [1]. The VASIMR concept involves a magnetic nozzle that shapes the ongoing plasma flow to provide its detachment from the rocket [2]. The detachment can occur after the energy density of the magnetic field drops below the kinetic energy density of the plasma flow [3]. At this point the magnetic field is no longer strong enough to control the flow. The transition from a region with a strong magnetic field to a region with a weak magnetic field corresponds to a transition from a sub-Alfvénic to a super-Alfvénic flow. Once the flow becomes super-Alfvénic, it stretches the magnetic field lines and keeps moving away from the rocket conserving its axial momentum. The super-Alfvénic transition is smooth if the guiding magnetic field lines are straight. We specify the restriction on the vacuum magnetic field configuration that ensures a smooth detachment. Sheared plasma flow is considered in an attempt to find the stability condition for the outgoing plasma flow.

This research is supported in part by Johnson Space Center, NASA.

[1] F.R.Chang-Dìaz, Sci. Am. **283**, 90 (2000).
[2] A.V.Arefiev and B.N.Breizman, Phys. Plasmas **5** (2004).
[3] E.B.Hooper, J. Propul. Power **9**, 757 (1993).

2C23

The Columbus Experiment*

M.F. SALVETTI and B.COPPI

Massachusetts Institute of Technology
Cambridge, Ma 02139

Abstract

The Columbus device is proposed as one component of a spectrum of experiments that are needed to explore the physics of fusion burning plasmas up to ignition. Columbus, which has a larger volume than Ignitor by about 50%, preserves the ability to confine, under macroscopically stable conditions, plasmas with peak pressures exceeding 3 MPa, corresponding to ignition at central plasma densities around 10^{21} nuclei/m^3 and to reach this regime by ohmic heating alone. A strong ohmic heating is to be maintained so that ignition can be reached even in the case of a failure of the ICRH system. The most important parameter design guideline is the value of the mean poloidal field ($\simeq 3.4T$). The plasma current $I_p \simeq 12.2MA$ is close to that of the ITER-Feat concept for the same value of the safety factor $q_{95}(\psi) \simeq 3.6$. As in the case of Ignitor and ITER-Feat, the plasma current redistribution time and the duration time of the plasma burning state are comparable. The Columbus program is proposed as a U.S. counterpart to the Ignitor program conducted in Italy and to be complementary to it. The machine costs and its development can be minimized by incorporating the main engineering solutions devised for Ignitor and taking advantage of the results of the R&D effort that has been carried out already.

[1] B. Coppi and M.F. Salvetti, MIT (RLE) Report PTP 02/06 (December
2002, Cambridge, MA)

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

2C24

Gyrokinetic Simulation of Microinstabilities in Generalized Toroidal Geometry

W.X. Wang[1], Z. Lin[2], S. Ethier[1], J.L.V. Lewandowski[1],
T.S. Hahm[1], W.W. Lee[1], G. Rewoldt[1], J. Manickam[1], W.M. Tang[1]

[1] *Princeton Plasma Physics Laboratory, P.O. Box 451*
Princeton, NJ 08543
[2] *University of California, Irvine, CA*

Abstract

An existing global gyrokinetic particle code (GTC) uses an advanced field-line-aligned mesh, a real space Possion solver and magnetic flux coordinates for the particle push. In order to address the plasma turbulence properties of realistic tokamak experiments, a general geometry capability is developed for GTC. It directly reads experimental plasma profiles and uses the corresponding numerical equilibrium. We make use of symmetry coordinates, which facilitate visualization and construction of a relatively regular mesh in real space for strongly shaped plasmas. Gyrokinetic transformation of potential and charge density between particle and guiding center positions in general geometry is carefully treated, taking into account finite B_θ/B. Trapped electron dynamics is included via higher order corrections to the adiabatic electron response. Cross benchmarks with the eigenvalue code, FULL, are carried out. Applications of the simulations of ion temperature gradient modes with trapped electron dynamics to conventional tokamaks, such as DIIID and JET, will be reported.

Work supported by U.S. DOE.

2C25

Mirror Mode Analysis for Magnetic Depressions in the Solar Wind [1]

H. Vernon Wong, W. Horton and M. J. Mithaiwala

Institute for Fusion Studies, University of Texas at Austin
Austin, TX 78712

Abstract

Regions of depressed magnetic fields, called "magnetic holes", have been observed in the solar wind, and *Winterhalter et al.*[1] have suggested that these magnetic depressions are the result of the mirror mode instability. Classical double adiabatic MHD theory, which assumes zero divergence of the parallel heat flux, predicts mirror instability when the pressure anisotropy $p_\perp/p_\| > 6$. However, as explained by Kulsrud, the instability threshold decreases from $p_\perp/p_\| > 6$ to $p_\perp/p_\| > 1$ when the divergence of the heat flux is included in a kinetic analysis for a uniform magnetic field [2]. The instability, near threshold, is a resonant particle instability involving low velocity particles along the field (*Southwood et al.*) [3]. Thus the pressure anisotropy (due to the majority non-resonant particles) is unlikely to change significantly as the instability grows. It is proposed that nonlinear saturation of the instability is due to the creation of local magnetic mirror wells in which particles become trapped, resulting in the reduction of the divergence of the parallel heat flux and the restoration of the instability threshold to a value between 1 and 6. The instability threshold , with particles trapped in local magnetic mirror wells, is estimated, and preliminary calculations indicate that the threshold increases from $p_\perp/p_\| > 1$ to $p_\perp/p_\| > 1.86$ as the fraction of trapped particles increases from zero to unity. Thus, if the initial pressure anisotropy is $1.86 > p_\perp/p_\| > 1$, the slowly growing mirror mode creates local magnetic mirrors that shuts off the instability when a significant fraction of particles are trapped.

[1] Winterhalter, D., M. Neugebauer, and B. E. Goldstein, et al., (J. Geophys. Res., 99), 23,371 -23,381, 1994.

[2] Kulsrud, R.M., *Handbook of Plasma Physics*, Vol. I, North-Holland Publishing Company, (1983).

[3] D. J. Southwood and M. G. Kivelson, (J. Geophys. Res., 98), 9181-9187, 1993.

[1]This work supported by the U.S. Dept. of Energy Contract No. DE-FG03-96ER-54346.

2C26

Turbulent saturation of tokamak core zonal flows

K. Hallatschek
Centre for Interdisciplinary Plasma Science, Max-Planck Institut für Plasmaphysik, EURATOM-IPP Association, D-85748 Garching, Germany, E-mail: hallatschek@ipp.mpg.de

Current theories of zonal flow generation and saturation focus on the radial transport of poloidal momentum. Different from a cylinder, stationary poloidal flows in a tokamak are accompanied by (possibly kinetic) return flows along the magnetic field, which cancel the flows' inherent divergence, maintaining incompressibility, and comprise the major part of the flow energy. In numerical ion temperature gradient turbulence studies, the turbulent diffusion of the parallel flow causes the flow saturation, whereas the poloidal momentum transport continues to strongly drive the flows.

2C27

Gyrokinetic Simulations of Plasma Transport and Isotope Effects*

C. Estrada-Mila,[1] J. Candy,[2] and R.E. Waltz[2]

[1]University of California. San Diego, California
[2]General Atomics, P.O. Box 85608, San Diego, California 92186-5608

Abstract

In this poster we present a systematic study of plasma transport, for both pure and impure plasmas, and isotope scaling using a computational approach. Historically, ion and more recently electron energy transport has been the focus of most simulations, while previous works on plasma flow emphasized impurity instability and flows with adiabatic electrons.[1]

Two codes were used for our studies: the reduced gyrofluid transport model GLF23,[2] and the Eulerian gyrokinetic code GYRO.[3,4] The latter includes trapped and passing electrons with pitch angle collisions, finite-β fluctuations, real flux-surface shape, linear and nonlinear E×B rotation, parallel shear flow and was recently modified to include multiple ion species with fully kinetic dynamics. The methodology employed for this research was to initially find interesting qualitative characteristics of the transport using GLF23, and subsequently analyze them in more detail using the quantitative realism of GYRO.

For the impurity flow study we made parameter scans for a mixture of deuterium with fully stripped helium, using the *Waltz Standard case*[2] as a reference point. The issues addressed in this presentation are the effects that impurity density gradient and the temperature gradient have on the transport. In particular, we explore the regimes where anomalous pinches (flow against primary gradients) are created. These results were used to make comparisons against the so called D-V model[5] where the total particle flux is the sum of a diffusive and convective part. Also, the passing and trapped particle contributions to pinch formation, in both pure and impure plasmas showing a roughly equal contribution from both in all cases analyzed. Finally, the question of validity of the dilution model, in which it is assumed that impurity species do not have a dynamical response, is considered. It is found that for realistic studies the model is not good above 10% impurity concentration.

The isotope scaling problem has also been analyzed from linear and nonlinear perspectives. We analyzed how the scaling of the growth rates for different type of plasmas is affected when kinetic electrons are included, and how the energy transport χ scales with $\mu = \sqrt{m_i/m_e}$. Also, investigate whether multi-isotope (e.g. 50%–50% D-T) plasmas have effects not previously considered.

[1]J.Q. Dong and W. Horton, Phys. Plasmas **2**, 3412 (1995).
[2]R.E. Waltz, *et al.*, Phys. Plasmas **4**, 2482 (1995).
[3]J. Candy and R.E. Waltz, J. Comput. Phys. **186**, 545 (2003).
[4]J. Candy and R.E. Waltz, Phys. Rev. Lett. **91**, 45001 (2003).
[5]M.R. Wade, *et al.*, Phys. Plasmas **2**, 2357 (1995).

*This was work supported by the U.S. Department of Energy under Grants DE-FG03-95ER54294, DE-FG03-95ER54309, and the SciDAC Plasma Microturbulence Project.

2C28

Magnetic Reconnection and Intrinsically Associated Thermal Energy Transport*

B. Coppi, V. Roytershteyn, and C. Yarim†

Massachusetts Institute of Technology, Cambridge, MA 02139 USA

The so-called drift tearing mode that was described first in Ref. [1] couples the effects of magnetic reconnection, driven primarily by the plasma current density gradient, with those of the gradient of the longitudinal electron pressure in a strongly magnetized plasma. We have pointed out originally that for modes involving singular perturbations the effects of nonlinearities become important at very small amplitudes. In order to analyze these effects we have started by reformulating the linearized theory of the drift tearing mode and considered, in general, the limit where the electron thermal conductivity along the field is significant. The nonlinear effects included in the simple model equation for the plane geometry that we analyzed are related to i) the (quasilinear) decrease of $dp_{e\parallel}/dx$ due to the effects of pre-excited modes, of the same kind, that couple with the considered mode and ii) the fact that $\hat{B}_x \partial \hat{p}_{e\parallel}/\partial x$ becomes important relative to $\mathbf{B}\cdot\nabla\hat{p}_{e\parallel} = i(\mathbf{k}\cdot\mathbf{B})\hat{p}_{e\parallel}$ as $\mathbf{k}\cdot\mathbf{B}$ tends to vanish within δ_L while $|\partial \hat{p}_{e\parallel}/\partial x|/|\hat{p}_{e\parallel}| \sim 1/\delta_L$ tends to become singular. Consequently, the width of the layer where these two effects are comparable can exceed easily that of the resistive reconnection layer [1] for quite small amplitudes of the reconnected field. The growth rate of the mode evaluated by the considered model equation is enhanced relative to that found by the linearized resistive theory. We note that tridimensional stability analyses concerning both cylindrical [2] and toroidal [3] configurations indicated that when the effects of the parallel pressure gradient are included, the rate of reconnection produced by the excited modes increases considerably, and the width of the reconnection region is definitely broader. In fact we consider that nonlinear drift-tearing modes can provide the explanation for modes involving magnetic reconnection that have been observed experimentally [4], and do not appear to correspond to neoclassical tearing modes.

References

[1] B. Coppi, Phys. Fluids, **8** 2273 (1965).
[2] A. Aydemir, Phys. Fluids B, **4** 3469 (1992).
[3] L. Sugiyama, et al., (to be published, 2004).
[4] J. A. Snipes, et al., Plasma Phys. Cont. Fus. **44**, 381 (2002).

* Sponsored in part by the U.S. Department of Energy
† On leave from I.T.U., Istanbul, Turkey

2C29

Helicity in two-dimensional cold-plasma linear mode conversion

Allan N Kaufman, UC Berkeley & LBNL
Alain J Brizard, St Michael's College
Eugene R Tracy, College of William & Mary

When plasma parameters, such as density $n(\mathbf{x})$ and magnetic-field strength $B(\mathbf{x})$, have non-parallel gradients in a mode-conversion region, the analysis of conversion cannot be reduced to the standard local one-dimensional slab model. For 2 spatial dimensions (such as a poloidal cross section of a tokamak), the ray phase space $(\mathbf{x},\mathbf{k})$ is 4-dimensional, and the rays lie in the 3-dimensional surface $D=0$, where D, the determinant of the WKB dispersion matrix $\mathbf{D}(\mathbf{k},\mathbf{x})$, is the ray Hamiltonian. In previous work [*Tracy & Kaufman*, PRL **91** (2003) 130402], we have shown that generically the rays are helical: in one 2-dimensional subspace of the 4-dimensional phase space, a ray orbit is hyperbolic, while in the other sub-space it is elliptic.

We apply these ideas to the simplest non-trivial model, representing a unidirectional magnetic field (in the $\hat{z}$-direction) $B(x,y)$ and plasma density $n(x,y)$, with their gradients non-parallel. (In particular, we consider the extreme case $B(x)$, $n(y)$.) We adopt the cold-plasma model in the ion-gyrofreqency range, with the wave electric field in the (x,y)-plane. For this model, we obtain an explicit expression for ray helicity. We calculate and display ray orbits, and exhibit and calculate their helicity.

The wave field $\mathbf{E}(x,y)$, associated with a set of ray orbits, is obtained by first performing a linear canonical transformation from $(\mathbf{x},\mathbf{k})$ to a new set of coordinates (q_1, q_2, p_1, p_2). In these coordinates, the ray Hamiltonian is separable: $D(\mathbf{q},\mathbf{p}) = D_1(q_1,p_1) + D_2(q_2,p_2)$. The related wave equation is separable, and can be solved in the conversion region in terms of standard functions. The wave field is then expressed in terms of these local solutions by a generalized Fourier transform. In this way, incoming eikonal waves can be split into transmitted and converted outgoing eikonal waves, even though the ray helicity in the conversion region complicates the analysis.

Sherwood Fusion Theory Conference, Missoula, MT, April 26-28, 2004
Research supported by US DOE/OFES.

2C30

MHD Numerical Simulations on Tetrahedral Grids with MH4D

Roberto Lionello, Dalton D. Schnack
Science Applications International Corporation
San Diego, CA 92121

Abstract

MH4D (Magnetohydrodynamics on a TETRAhedral Domain) is a massively-parallel, device-independent numerical code for the solution of the resistive and viscous MHD equations on an unstructured grid of tetrahedra. The unstructured grid allows the computational domain to be of arbitrary shape and the resolution to be increased in the regions of physical interest. Consequently, plasma confinement devices of complex shape (e.g. stellerators) can be modeled and problems with a wide range of spatial scales can be studied. A variational formulation of the differential operators ensures accuracy and the preservation of the analytical properties of the operators ($\nabla \cdot \mathbf{B}=0$), and self-adjointness of the resistive and viscous operators. The combined semi-implicit treatment of the waves and implicit formulation of the diffusive operators can accommodate the wide range of time scales present in the solar corona. The capability of mesh refinement and coarsening is also included. MH4D is capable of solving the full resistive and viscous MHD equations both explicitly and semi-implicitly. We will present new results obtained with the full MHD code such as a simulation of the nonlinear kink in the line-tied Gold-Hoyle equilibrium [1,2] and a solution of the coplanar MHD Riemann problem of Brio and Wu (1988) [3].

[1]T. Gold and F. Hoyle, Mon. Not. R. Astron. Soc., **120**, 89 (1960)
[2]R. Lionello, Z. Mikić, and D. D. Schnack, J. of Comput. Phys., **75**, 400 (1998)
[3]M. Brio and C. C. Wu, J. of Comput. Phys., **140**, 172 (1998)

2C31

L$\rightarrow$H transitions and transport barrier propagation in a simple model of coupled heat and particle fluxes

M.A. Malkov and P.H. Diamond

University of California at San Diego, 9500 Gilman Dr, La Jolla, CA 92093-0319, USA

Abstract

The origin and structure of edge [1] and internal [2] transport barriers is one of the central problems in magnetic fusion research. A simplified model proposed in [3] includes coupling between the nonlinear fluxes of particles and heat in a form of two diffusion equations. Earlier, we solved this model analytically in a steady state assuming that regularization (taken in a form of hyperdiffusion) is applied to only one field (density or pressure). In this simple case the transition is shown to obey the Maxwell equal area rule. However, different regularization schemes result in different transition rules. We have shown that inclusion of the curvature of radial pressure profile, for example, leads to a criterion that the transition occurs at lower heat and particle fluxes. This dependence of transition criteria on the regularization clearly demonstrates the necessity of dynamical modelling. In this paper, we therefore also explore a time dependent approach. In particular we discuss the front propagation solutions describing the penetration of the H-mode state into L-mode state and vice versa.

[1] Wagner F, et al., **49**, PRL, 1408 (1982)
[2] Koide, Y. et al. PRL, **72**, 3662 (1994)
[3] Hinton, F. L. and Staebler, G.M. Phys. Fluids, 1281 (1993)

2C32

Effect of Toroidicity on Fast Fuel Relocation in Tokamaks*

P.B. Parks[1] and L.R. Baylor[2]

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA
[2]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37381, USA

Abstract

Pellet injection from the inner midplane region, or high-field-side (HFS) of a tokamak promotes a deeper fuel deposition profile, well beyond the pellet penetration depth. The effect stems from the inhomogeniety of the toroidal magnetic field, which causes an inward $E\times B$ advection of the high-pressure ablation plasmoid, polarized by the magnetic drift currents. Three important new mechanism have been identified, which extend the previous analytical theory of the advection process: 1) Mach Number Effect. The parallel expansion velocity of the plasmoid ranges from subsonic to supersonic, with respect to the sound speed of the plasmoid, and it is thus the only near-sonic flow in a tokamak. This unusual result, means that the centrifugal force arising from $M \sim 1$ parallel flows, coupled with the curvature of the (largely) toroidal magnetic field, will drive a significant *additional magnetic curvature drift current* inside the plasmoid. Since the parallel flows persist long after the plasmoid pressure has relaxed towards the background plasma pressure, the curvature effect still continues to power the $E\times B$ drift, and consequently it significantly *lengthens the fuel penetration depth.* 2) Toroidicity This geometrical effect results from the expansion of the plasmoid along a helical magnetic flux tube, while it drifts inward. At any moment, the electrostatic potential $\Phi(x,y)$ in the plasmoid is assumed to be uniform along a given field line defined by a point in the orthogonal field line following (FLF) coordinate system (x,y), with x pointing in magnetic flux direction. Consequently, the internal electric field E must rotate with respect to the fixed vertical grad-B drift direction with increasing distance z along the field lines inside the plasmoid. *This reduces the drift velocity and penetration.* 3) Mass Shedding Magnetic shear makes the cloud and flux-tube cross section threading the cloud become more elliptical with increasing distance z along the field lines, while preserving the cross-sectional area. After the cloud has expanded to a distance of order of the magnetic shear length $L_S = qR/\hat{s}$, where $\hat{s} = (r/q)q'$ is shear parameter, elliptical compression and rotation in the FLF coordinates orients the polarization charge layers in different directions as z increases. This result in a differential drift of the cloud segments: the end parts of the cloudlet can drift to flux tubes out of the electrostatic region of influence and "peel off" one by one. This dispersal effect *spreads out the fuel deposition profile*. The new theory was incorporated in the Pressure Relaxation Lagrangian Code (PRL), which solves for the 1-D parallel expansion dynamics and couples it to the analytic solution of the parallel vorticity equation describing the cross-field incompressible flows $\nabla \cdot (\vec{v}_\perp / R^2)$ associated with the coherent $E\times B$ drift motion. The cloud pressure reaches equilibrium after a several sound times $\sim 5L_c/c_s$ where $L_c = (r_\perp R)^{1/2}$ is the initial cloud half-length, at which point the plasmoid temperature is only ~20–40 eV which agrees with experimental measurements. A comparison between the measured Δn deposition profile following HFS pellet injection on the DIII-D tokamak and the PRL code result show reasonably good agreement, considering that the pellet was actually injected from 30 cm above the midplane. A preliminary simulation for ITER shows deep fueling is possible.

*This was work supported by the U.S. Department of Energy under Grant DE-FG03-95ER54309 and DE-AC05-00OR22725.

2C33

Impact of Shear Flow on Turbulent Transport in a Neutral Fluid

J. Sauer,[1] A. S. Ware,[1] D. E. Newman,[2] P. W. Terry,[3] and M. H. Hitchman[3]

[1] *University of Montana, Missoula, MT 59812-1080*
[2] *University of Alaska-Fairbanks, Fairbanks, AK 99775*
[3] *University of Wisconsin-Madison, Madison, WI 53706*

Abstract

Numerical simulations of a geostrophic vorticity equation are presented. In large-scale atmospheric flows, the Earth's rotation stratifies the flow, inducing two-dimensional behavior in the flow. The Earth's rotation also stabilizes large-scale flows that would otherwise be unstable to Kelvin-Helmholtz instabilities, similar to the effect of the magnetic field in magnetized plasma flow. We present two types of numerical simulations of two-dimensional geostrophic flow: a pseudospectral model (PSM) [1] and a finite-elemental model (FEM) which uses the FEMLAB [2] software. Previous work using just the pseudospectral model has shown that the straining by a sheared, barotropically stable, large scale jet, leads to a reduction of the cross-flow scale of turbulent flow. This reduction is a result of the combined effect of shear straining by the jet which is dominant at large scales and turbulent decorrelation which is dominant at small scales. This is isomorphic to the reduction of turbulent transport in a plasma by sheared E□B flows. Here, results from the PSM are compared with results from the FEM simulations. Using the FEM method also allows for the possibility of testing the impact of a linear shear flow on turbulent transport (which is not possible in a spectral or pseudospectral code).

[1] A. S. Ware, P. W. Terry, M. H. Hitchman, and D. E. Newman, "The role of shear flow in stratospheric transport barriers", *Proceedings of the 10th Conference on Waves and Stability*, (1994).
[2] FEMLAB

MHD stability of low-n modes in small aspect ratio tokamaks

J. Breslau[1], W. Park[1], H. Strauss[2], L. Sugiyama[3], J. Chen[1], S. Jardin[1]
[1]Princeton Plasma Physics Laboratory
Princeton, NJ 08543-0451
[2]Courant Institute, New York University
New York, NY 10012-1185
[3]Plasma Science and Fusion Center, Massachusetts Institute of Technology
Cambridge, MA 02139

Abstract

We apply the M3D code [1] to the study of the dominant global instabilities in typical discharges in small aspect ratio tokamaks such as the Current Drive Experiment Upgrade (CDX-U). Equilibria with $q_0 \approx 0.95$ (and thus a $q=1$ rational surface no more than one-third of a minor radius out from the magnetic axis) exhibit a spectrum of linearly MHD-unstable modes with toroidal mode numbers $n=1$ and up, with the higher-n modes having higher growth rates, as previously observed in results from the NIMROD code [2]. Eigenmodes for low n (≤ 3) typically cluster mainly at the $q=1$ rational surface, while for larger n the high resistivity of the low-temperature plasma at higher-q surfaces further from the plasma core results in high poloidal mode number m resistive ballooning modes about those surfaces.

We next investigate the nonlinear behavior of the low-n modes. The traditional expectation for the nonlinear evolution of the $m=1$, $n=1$ mode is that it will result in one or a series of sawtooth crashes, reconnection events that flatten the temperature profile and restore the equilibrium and may also nonlinearly trigger the formation of the higher-m seed islands of neoclassical tearing modes. While we observe this phenomenon under some conditions, there are a number of cases in which we instead find that the $n=1$ mode itself comprises a full spectrum of coupled poloidal modes at many rational surfaces. These modes can grow to substantial sizes before a single sawtooth crash occurs, thus providing an alternate mechanism for the generation of the seed islands. The implications of this MHD result are explored.

We also consider two-fluid effects, which are particularly pronounced in low-density, small major radius discharges such as those in CDX-U, and may change both the foregoing linear and nonlinear pictures considerably by stabilizing the higher-n modes. The effects of equilibrium flow on the stability of these modes are also considered.

[1]W. Park, et al., *Phys. Plasmas* **6**, 1796 (1999).
[2]D. Schnack, personal communication (2003).

Nonlinear Evolution of Magnetic Shear-Localized Interchange Instabilities

Sangeeta Gupta, J. D. Callen and C. C. Hegna
Department of Engineering Physics, 1500 Engineering Drive
University of Wisconsin, Madison, Wisconsin 53706-1609

The Suydam's/Mercier criterion ($D_I < 1/4$) defines the stability boundary of a toroidally confined plasma for a magnetic shear localized ideal MHD pressure driven interchange instability. The linear stability analysis of these instabilities indicates a very weakly growing mode well above the marginal stability condition[1]. The nonlinear regime of these weakly growing instabilities will be presented in this work. For studying the nonlinear dynamics of these modes, the nonlinear vorticity equation, Ohm's law and pressure evolution equations are solved numerically in two spatial dimension. The perturbed quantities are expanded in Fourier modes in y direction. Then, each Fourier mode is evolved in both space x ("radial", pressure gradient direction) and time. Numerical results indicates that the instability saturate at low amplitude with the formation of current sheet at $ky = \pi/2$. Here, the magnetics plays a dominant role in the saturation of instability in contrast to the usual pressure flattening mechanism in the magnetic shear free interchange instability. In the nonlinear phase, the vorticity equation evolves as $d\nabla_\perp^2 \tilde{\phi}/dt \simeq 0$ which implies that the pressure gradient drive is balanced by magnetic field line bending. In this limit, pressure profile can be solved exactly and given by $\tilde{p} = X \pm \sqrt{X^2 - 2\tilde{\psi}}$ where $\tilde{\psi}$ is the perturbed magnetic flux function. Thus, from the vorticity equation, we get a grad shafronov type "equilibrium" equation in the presence of pressure gradient drive as

$$\nabla^2 \tilde{\psi}_N \mp \frac{D_I X}{\sqrt{2\tilde{\psi}_N}} = f(\tilde{\psi}_N)$$

where $\tilde{\psi}_N = X^2/2 - \tilde{\psi}$. The possible solution of this equation will be presented.

[1]Sangeeta Gupta, J. D. Callen and C. C. Hegna, "Violating Suydam criterion produces feeble instabilities," Phys. Plasmas **9**, 3395 (2002).

2C36

Transport in High Density Igniting Plasmas*

F. Bombarda[1], B. Coppi[2], P. Detragiache[1], M. Romanelli[1]

[1]Associazione ENEA – Euratom sulla Fusione, Italy
[2]Massachusetts Institute of Technology, Cambridge, USA

On the basis of presently known stability and transport properties of magnetically confined plasmas, ignition can be achieved with the highest probabilities in compact, high field, high density devices. Ignitor is characterized by a toroidal field $B_T \leq 13$ T, compact dimensions ($R_0 \cong 1.32$ m), a relatively low aspect ratio ($R_0/a \cong 2.8$), and a considerable plasma elongation and triangularity ($\kappa \cong 1.83$, $\delta \cong 0.4$). The reference central density is about 10^{21} m^{-3}, and the plasma current $I_p \cong 11$ MA. Confinement and transport issues for Ignitor can be investigated in existing high field, high density experiments such as FTU (Frascati Tokamak Upgrade), which can operate in a region of parameters complementary to that of most other existing devices. In particular, the scaling of confinement with density at high fields has been addressed in recent FTU experiments for B_T=7.2 T, I_p=0.8 MA. As was already observed in other high field machines, the energy confinement time τ_E increases with density up to a saturation value corresponding to those of the so-called L-mode regime when the density profiles are relatively flat. The injection of pellets to prevent the confinement saturation was suggested for the Alcator C experiment to stabilize the Ion Temperature Gradient (ITG) driven modes by means of an adequate density gradient. In FTU plasmas with multiple pellet injection the linear trend of the neo-Alcator scaling is extended and τ_E reaches values in excess of 100 ms [1], about 30% above the ITER-97L scaling, for n_{e0} as high as 8×10^{20} m^{-3}, close to the Ignitor reference central density. The corresponding effective thermal diffusivity $\chi^{\text{eff}} \cong a^2/4\tau_E \cong 0.2$ m^2/s is within the range of the values estimated for Ignitor in order to reach ignition, on the basis of current thermal transport models. The possibility of achieving H-mode confinement in Ignitor has been also investigated for a double null configuration with the X-points laying on the first wall and with $I_p \cong 9$ MA, and $a \cong 0.44$ m. A zero-dimensional analysis based on the global plasma power balance equation shows that, for moderately peaked plasma pressure profiles, operation at Q=10 is possible at densities about half the reference value. By increasing the density, operation at higher values of Q is also possible.

*Sponsored in part by C.N.R. (Italy), E.NE.A. (Italy) and the U.S. Department of Energy

[1] B. Esposito, M. Marinucci, M. Romanelli *et al* (2004), submitted *to Plasma Phys. Contr. Fusion*

2C37

Spectral modeling of nonlinear plasma evolution in compact toroids*

Preston Geren[1] and Loren Steinhauer[2]

[1]Geren Consulting Services, Shoreline, Washington
[2]University of Washington, Redmond, Washington

Abstract

In incompressible plasmas the magnetic and flow fields are divergence free. Therefore both **B** and **u** can be expanded in a divergence-free basis set of vectors. A complete basis set is provided by the Beltrami functions, which are solutions of the Beltrami equation $\nabla\times\mathbf{Y} = \Lambda\mathbf{Y}$. For a domain with boundary condition of no normal component at the surface $\mathbf{Y}\cdot\mathbf{n} = 0$, these become discrete eigenvectors $\mathbf{Y}_k$ associated with the eigenvalues Λ_k. The equations of motion of a fluid plasma (either a single fluid or a two fluid) can be expressed as a coupled system of first order differential equations for the expansion coefficients $B_k(t)$ and $u_k(t)$. This approach can be used to model the nonlinear dynamics of plasmas in a compact geometry. The boundary condition ($B_n = u_n = 0$) is appropriate for modeling internal dynamics, i.e. the separatrix is regarded as a rigid boundary. The periodic domain can have arbitrary elongation.

For the periodic cylinder domain analytic solutions are available for the eigenvectors. Computed results will be presented for the periodic cylinder. These computations can be used to model the nonlinear development of well-known global modes such as tilting. In this way the nonlinear stability of a compact toroid plasma, including nonlinear mode-mode coupling can be investigated. To be addressed will be such important questions as spontaneous flow generation, the nonlinear stability of flowing equilibria, the ruggedness of the ideal invariants in the presence of a small dissipation, and the emergence of a quasi-steady turbulence spectrum. Also, the end-point of a relaxation can be determined. This should permit which of the several relaxation principles best represents the actual plasma behavior.

*Supported by USDOE grant No. DE-FG03-98ER54480

A fully implicit 3D MHD Newton-Krylov algorithm: a numerical proof-of-principle

L. Chacón, D. A. Knoll

Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract

Extended magnetohydrodynamics (XMHD) includes nonideal effects such as nonlinear, anisotropic transport and two-fluid (Hall) effects. XMHD supports multiple, separate time scales that make explicit time differencing approaches extremely inefficient. While a fully implicit implementation promises efficiency without sacrificing numerical accuracy,[1] the nonlinear nature of the XMHD system and the numerical stiffness associated with the fast waves make this endeavor difficult.

Newton-Krylov methods are, however, ideally suited for such a task. These synergistically combine Newton's method for nonlinear convergence, and Krylov techniques to solve the associated Jacobian (linear) systems. Krylov methods can be implemented Jacobian-free and can be preconditioned for efficiency. Successful preconditioning strategies have been developed for 2D incompressible resistive[2] and Hall[3] MHD models. These are based on "physics-based" ideas, in which knowledge of the physics is exploited to derive well-conditioned (diagonally-dominant) approximations to the original system that are amenable to optimal solver technologies (multigrid).

Recently,[4] a novel finite-volume discretization for implicit 3D MHD applications has been developed for general, non-orthogonal geometries that is: 1) conservative, 2) solenoidal in $\vec{B}$ and $\vec{J}$, 3) numerically non-dissipative, and 4) linearly and nonlinearly stable in the absence of physical dissipation. A fully implicit Newton-Krylov solver has been developed for 3D single-fluid MHD using this discretization concept. A physics-based preconditioner, developed by extending the ideas put forth in [2,3], has been implemented. Multigrid methods are employed to solve the required systems in the preconditioning stage. We will present preliminary numerical results of the performance of the implicit solver in simple geometries.

[1] D. A. Knoll et al., *J. Comput. Phys.* **185** (2), 583-611 (2003)
[2] L. Chacón et al., *J. Comput. Phys.* **178** (1), 15-36 (2002)
[3] L. Chacón and D. A. Knoll, *J. Comput. Phys.*, **188** (2), 573-592 (2003)
[4] L. Chacón, *J. Comput. Phys.*, submitted (2004); L. Chacón, D. A. Knoll, *Bull. Am. Phys. Soc.*, FP1 108, 116 (2003)

2C39

Two-fluid magnetic reconnection with arbitrary guide-field

Richard Fitzpatrick
IFS, UT Austin

The following new set of reduced equations governing 2-D, two-fluid, magnetic reconnection with arbitrary guide-field is derived:

$$\begin{aligned}
\frac{\partial \psi_e}{\partial t} &= [\phi, \psi] + d_\beta\,[\psi, Z] + \eta\,\nabla^2\psi,\\
\frac{\partial Z_e}{\partial t} &= [\phi, Z] + d_\beta\,[\nabla^2\psi, \psi] + c_\beta\,[V_z, \psi] + c_\beta^2\,\eta\,\nabla^2 Z,\\
\frac{\partial U}{\partial t} &= [\phi, U] + [\nabla^2\psi, \psi] + \mu\,\nabla^2 U,\\
\frac{\partial V_z}{\partial t} &= [\phi, V_z] + c_\beta\,[Z, \psi] + \mu\,\nabla^2 V_z,
\end{aligned}$$

where ψ is the magnetic flux-function, ϕ the ion stream-function, Z the normalized perturbed magnetic field in the z-direction, $U = \nabla^2\phi$, $\psi_e = \psi - d_e^2\,\nabla^2\psi$, and $Z_e = Z - c_\beta^2\,d_e^2\,\nabla^2 Z$. Also, $[A, B] \equiv \nabla A \wedge \nabla B \cdot \hat{\mathbf{z}}$. Here, $c_\beta = \sqrt{\beta/(1+\beta)}$, $d_\beta = c_\beta\,d_i$, where β is the plasma beta calculated with the guide-field, d_i the collisionless ion skin-depth, and d_e the collisionless electron skin-depth. It is assumed that $\partial/\partial z \equiv 0$. The reduction process involves the removal of the compressible Alfvén wave, which plays no role in magnetic reconnection.

The above equations, which are easy to solve numerically, represent a significant advance in magnetic reconnection theory, since all existing sets of reduced equations used to study reconnection are only valid in either the large or the small guide-field limits (*i.e.*, either $\beta \gg 1$ or $\beta \ll 1$). The new equations are used to investigate the scaling of the rate of forced magnetic reconnection in the so-called Taylor problem, in which a tearing stable plasma is subject to a suddenly applied resonant magnetic perturbation. In the non-linear regime with arbitrary guide-field (and $d_e = 0$), the peak reconnection rate is independent of the resistivity, and scales like $d\Psi/dt \sim [\beta/(1+\beta)]^{3/4}\,d_i^{3/2}\,\Xi_0^2$, where Ξ_0 the amplitude of the external perturbation. This result cannot be accounted for in terms of the "universal" reconnection rate recently proposed by the Maryland group.

2C40

Action Principle Derivation of Reduced Fluid Models

Alexander Wurm* and P.J. Morrison
Institute for Fusion Studies and Department of Physics
The University of Texas at Austin
Austin, TX 78712

Abstract

It is well-known that ideal MHD possesses an action principle formulation when it is expressed in terms of Lagrangian (or material) variables, and similar action principles exist for magnetofluid models that include more general equations of state (CGL) or more sophisticated means for momentum transport (gyroviscosity). Starting from these action principles we derive various reduced Hamiltonian models such as reduced MHD and other gyroviscous fluid models.

[1] W.A. Newcomb, Nuclear Fusion: 1962 Suppl. Part 2, p. 451.

* Supported by an appointment to the U.S. Department of Energy Fusion Energy Postdoctoral Research Program administered by the Oak Ridge Institute for Science and Education.

Gyrokinetic Simulations of Neoclassical Flows Embedded in Turbulence*

R.E. Waltz, J. Candy, and F.L. Hinton

General Atomics, P.O. Box 85608, San Diego, California 92186-5608

GYRO is a comprehensive nonlinear continuum (Eulerian) gyrokinetic code which can treat either gyroBohm scaled flux tubes at vanishing ρ_* or full-radius core profiles at small but finite ρ_*. It contains all the physics presently thought to be needed for physically realistic simulations of the tokamak core: toroidal ion temperature gradient (ITG) mode physics, trapped and passing electrons, electron-ion pitch angle collisions, electromagnetic effects up to the ideal beta limit, real geometry, E×B and magnetic flutter transport. GYRO operating in a nearly full radius slice at finite ρ_* and has both E×B and diamagnetic rotational shear stabilization which can effectively break gyroBohm scaling.[1] Parallel rotational shear drive from the toroidal rotation is also included. GYRO has been used to simulate the DIII-D L-mode dimensionally similar ρ_* pair with Bohm scaling.[2] Using experimental profiles, simulated power flows are within twofold of experimental flows and 10% adjustment of the ion temperature gradients can bring them into agreement. Multiple ion species have been added and impurity and plasma flow studies are underway. Recently neoclassical flows and drivers have been added.

In previous work, Wang *et al.* used a global PIC n=0 gyrokinetic code to simulate large banana orbit neoclassical flows.[3] (n is the toroidal mode number.) The present work includes all n and focuses on the interaction of $|n| \geq 0$ turbulence and n=0 neoclassical flows. Turbulent E×B and magnetic flutter radial transport flows, $\langle(\tilde{\upsilon}_E \cdot \nabla r)\tilde{f}\rangle$ and $\langle(\upsilon_\parallel \tilde{B}_\perp / B_0 \cdot \nabla r)\tilde{f}\rangle$ are driven by the ω_* terms $(\tilde{\upsilon}_E \cdot \nabla r)F_M$ and $(\upsilon_\parallel \tilde{B}_\perp / B_0 \cdot \nabla r)F_M$ in the $|n| > 0$ gyrokinetic equations. ($\langle\ \rangle$ denotes flux surface average, $\tilde{f}$ is the perturbation from the Maxwellian distribution function F_M). The neoclassical curvature drift velocity (υ_D) flows $\langle(\upsilon_D \cdot \nabla r)\tilde{f}\rangle$ are driven by $(\upsilon_D \cdot \nabla r)F_M$ in the n=0 gyrokinetic equation for $\tilde{f}$ when ion-ion collisions are included. Global simulations will approach the cyclic flux tube simulations in the limit of vanishing ρ_*. We denote perturbations by $f_{n,p}(\theta)$ where p is the radial wave number harmonic with p=0 the longest scale. The neoclassical flows and driver involve only (n,p) = (0,0) and turbulence involves all others. In the vanishing ρ_* limit where the parallel nonlinearities vanish, it is easy to show there is no interaction between turbulent and neoclassical transport. Advancing only the (n,p) = (0,0) component (normally excluded from cyclic flux tubes), GYRO can recover the standard small orbit neoclassical radial flows as well as ion parallel flows and bootstrap current. We include an electron-ion drag and test number, energy, and momentum conserving Krook as well as pitch-angle scattering ion-ion collision operators. The radial electric filed is input with density and temperature gradients. There is no perturbed electric field. These flows are then compared with those with the local radially averaged flows in simulations of finite-ρ_* (large banana orbit) global profile slices with and without interaction with the turbulence induced by the finite-n modes. Perturbed electric fields then are obtained from the (polarized) quasi-neutrality equation. We examine the effect of the neoclassical driver on the turbulent transport and n=0 zonal flows.

[1] R.E. Waltz, J. Candy and M.N. Rosenbluth, Phys. Plasmas **9**, 1938 (2002).

[2] J. Candy and R.E. Waltz, Phys. Rev. Lett. **91**, 045001 (2003).

[3] W.X Wang, F.L. Hinton, and S.K. Wong, Phys. Rev. Lett. **87**, 055002-1 (2001)

*This was work supported by the U.S. Department of Energy under Grant DE-FG03-95ER54309 and the SciDAC Plasma Microturbulence Project.

2C42

Heat Flux Transport in Stochastic Magnetic Fields with Line Tying S.E. KRUGER, Tech-X Corporation, D.D. SCHNACK, SAIC — Understanding the onset and nonlinear dynamics of disruptions is crucial for preventing or mitigating them in next-step devices. Initial-value simulations with the NIMROD code of an ideal-MHD unstable plasma based on DII I-D discharge #87009 allows for detailed studies of the dynamical mechanisms of the disruption and the resulta nt heat flux distribution on the wall. The ideal mode grows and causes 2/1 magnetic islands as a result of for ced reconnection at the two 2/1 surfaces. The mode amplitudes continue to grow until the magnetic islands ove rlap and the magnetic field is stochastic over a large part of the plasma domain. The rapid stochastization o f the field allows the plasma to lose two thirds of its internal energy in approximately 200 microseconds in q ualitative agreement with the experiment. The deposition of thermal energy on the wall is localized poloidall y and toroidally on the wall due to helically-localized temperature increases and parallel heat flux carrying this increased heat flux to the wall. Understanding the heat flux localization requires a detailed understand ing of the three-dimensional field line structure as the plasma undergoes changes in topology. In this work, we focus on visualizing and understanding the changes in topology.

2C43

Onset of the thermonuclear instability and Oscillatory States near Ignition

A. Airoldi[1], G. Cenacchi[2] and B. Coppi[3]

[1]Consiglio Nazionale delle Ricerche – Roma, Italy
[2]E.N.E.A. – UTS Fusione Ignitor, Frascati, Italy
[3]Massachusetts Institute of Technology, Cambridge, MA 02139

Ignition, that is the condition when the nuclear plasma heating equals the rate of plasma energy loss, can be achieved in high magnetic field experiments such as Ignitor at relatively low peak temperatures [1]. At this stage of the plasma heating cycle the thermonuclear instability can develop. The aim of analysis that is presented is to identify the conditions under which the instability can be prevented from producing an excessive temperature excursion and where an oscillatory state, corresponding to values of the fusion criticality parameter P_α / P_{loss} slightly lower than unity, can be achieved (under quasi steady state conditions characterized by $P_{fusion} / P_{input} > 10$). The considered plasma thermal diffusivity and degree of plasma purity are consistent with those obtained by high magnetic field experiments (most recently by the FTU machine), in which high densities with peaked profiles have been produced by repeated pellet injections, as planned for Ignitor. In fact oscillatory states have been produced rather easily by our numerical simulations, carried out by the 1-1/2D JETTO transport code, in subignited regimes where proper combinations between the tritium to deuterium ratio and additional ICRH pulses are used to maintain these quasi-stationary states.

Moreover a set of representative nonlinear equations designed to describe an oscillatory state near ignition has been formulated. This produces a relatively rapid sequence of temperature rises, due to nuclear heating, and crashes due to an instability driven by the plasma pressure gradient in the central region of the plasma column. The pressure profile from which this sequence starts is the "canonical" profile that has been identified [2] as being reached at ignition under a variety of conditions for high density plasmas (i.e. peak densities around $10^{21}\ m^{-3}$)

*Sponsored in part by C.N.R. (Italy), E.N.E.A. (Italy) and the U.S. Department of Energy

[1] B. Coppi, A. Airoldi, F. Bombarda et al, *Nuclear Fusion* **41**, 1253 (2001).
[2] A. Airoldi and G. Cenacchi, *Nuclear Fusion* **41**, 687 (2001)

2C44

Gyrokinetic Particle-In-Cell Calculations of Ion Temperature Gradient Driven Turbulence with Parallel Nonlinearity and Strong Flow Corrections*

James C. Kniep, Jean-Noel Leboeuf and Viktor K. Decyk
Department of Physics and Astronomy
University of California at Los Angeles
Los Angeles, CA 90095-1547

Abstract

Nonlinear gyrokinetic calculations have been performed with the three-dimensional, global, toroidal, particle-in-cell, delta-f, UCAN code[1] to study the effects of parallel nonlinearity and strong (externally imposed) flow corrections on ion temperature gradient driven turbulence. These calculations are electrostatic and adiabatic electrons are used. An equilibrium ion temperature gradient only is imposed, along with a generic parabolic q-profile appropriate to a large aspect ratio tokamak. The strong flow corrections derived by T. S. Hahm[2] have been added to the usual orbit and weight equations used in the UCAN code. The parallel nonlinearity[3] has been reactivated as well in the same equations. To examine the effect of strong flow corrections, the calculations have been performed with fluctuations-generated flows or zonal flows arbitrarily set to zero but with externally imposed sheared flows obeying a variety of profiles more or less localized in radius and with various flow magnitudes. The calculations show that the strong flow corrections have a qualitative effect on the saturation level of the fluctuations and on the steady-state heat flux even at the highest flow magnitudes used. The calculations with the re-activated parallel nonlinearity have been performed with no externally imposed flow but with fluctuations-generated or zonal flows allowed to self-consistently evolve. The parallel nonlinearity makes a quantitative difference in the saturation level of the fluctuations and in the saturated flux, as reported by Villard and colleagues[3]. This difference does however appear to diminish as the system size is increased at fixed ion gyroradius. Results of convergence studies with increasing system size and with varying degrees of self-similarity in profiles and parameters will be presented.

[1] R. D. Sydora, V. K. Decyk, and J. M. Dawson, "Fluctuation-induced heat transport results from a large global 3D toroidal particle model", Plasma Physics and Controlled Fusion **38**, A281-94 (1996); J.-N. Leboeuf, J. M. Dawson, V. K. Decyk, M. W. Kissick, T. L. Rhodes, and R. D. Sydora, "Effect of externally imposed and self-generated flows on turbulence and magnetohydrodynamic activity in tokamak plasmas", Phys. Plasmas **7**, 1795-1801 (2000).

[2] T. S. Hahm, "Nonlinear gyrokinetic equations for turbulence in core transport barriers", Phys. Plasmas **3**, 4658-4664 (1996).

[3] L. Villard, S. J. Allfrey, A. Botino, M. Brunetti, G. L. Falchetto, V. Grandgirard, R. Hatzky, J. Nuhrenberg, A. G. Peeters, O. Sauter, S. Sorge, and J. Vaclavik, "Full radius linear and nonlinear gyrokinetic simulations for tokamaks and stellarators: Zonal flows, applied ExB flows, trapped electrons and finite beta", Nucl. Fusion **44**, 172-180 (2004).

* Work supported at UCLA by USDOE Grant No. DE-FG02-04ER54740. This work is also part of the SciDAC Plasma Microturbulence Project.

2C45

A Gyro-Landau-Fluid Model for Trapped and Circulating Particles*

G.M. Staebler,[1] J.E. Kinsey,[2] and R.E. Waltz[1]

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608
[2]Lehigh University, Bethlehem, Pennsylvania

Abstract

Gryo-Landau-Fluid (GLF) models have been shown to give an accurate approximation to the kinetic linear growth rates of drift-ballooning modes in Tokamaks.[1-3] GLF models for separate passing and trapped fluids with collisional exchange were the bases of the successful quasilinear transport model GLF23.[4] However, GLF23 is limited to a small range of magnetic shear and to shifted circle geometry due to its use of a trial wave function fitted to obtain growth rates approximating exact kinetic results. A Hermite basis function method for solving the GLF eigenmode equations has been developed to replace the trail wavefunction approach. Experimental situations in which both electron and ion modes are unstable in overlapping wavenumber ranges are not uncommon. GLF23 assumed a stable gap between the electron temperature gradient (ETG) and ion temperature gradient (ITG) modes. Treating the overlapping case requires a new set of GLF equations. A new system of GLF equations is presented here with three moments for trapped particles and six moments for passing particles. The trapped particles have only even moments since the odd moments are assumed to be bounce averaged to zero. The closure of the highest moments yields coefficients which are functions of the trapped particle fraction. These coefficients are fit by minimizing the error between the GLF response functions and the exact kinetic result as was done in Ref. 3 for a six moment gyrofluid model for circulating particles. A model for the boundary between those trapped particles which can bounce average a given wave and those which can have a Landau resonance with the wave is used. This model gives the fraction of bounce averaging particles which is a functions of the parallel wavenumber of the wave but not its frequency. Using this bounce averaging fraction in place of the trapped fraction gives a model which is valid over the full spectrum of driftwave eigenmodes and is not restricted to modes with frequency below the bounce frequency. Thus, the final system of GLF equations for ions and electrons is valid from the lowest frequency trapped ion modes all the way up to the highest frequency ETG modes. Benchmarking of the linear growth rates with a large database of gyrokinetic growth rates will be shown. The implications of the overlapping of electron and ion instabilities on transport will be explored at the quasilinear level with the new model. The GLF model gives a much faster calculation of the linear eigenmodes than a gyrokinetic initial value code. The new GLF model has applications as an analysis tool for experimental discharges (both growth rates and critical gradients) and as the core eigenmode solver in a quasilinear transport model [4].

[1]G.W. Hammett and F.W. Perkins, Phys. Rev. Lett. **64**, 3019 (1990).
[2]R.E. Waltz, R.R. Dominguez and G.W. Hammett, Phys. Fluids **B4**, 3138 (1992).
[3]M.A. Beer and G.W. Hammett, Phys. Plasmas **3**, 4046 (1996).
[4]R.E. Waltz, *et al.*, Phys. Plasmas **4** (1997) 2482.

*This was work supported by the U.S. Department of Energy under Grants DE-FG03-95ER54309 and DE-FG02-92ER54141.

2C46

Plasma Response to Waves in Arbitrary Magnetic Field Geometry

Brent Goode[1], J.R. Cary[1], L.A.Berry[2]

[1.] Center for Integrated Plasma Studies, University of Colorado
Boulder, CO 80302
[2.] Oak Ridge National Lab
Oak Ridge, TN 37831

Abstract

We examine the effects of non-uniform magnetic fields on the propagation and absorption of RF waves in plasmas. The effects we include are curvature, and gradients in field strength in arbitrary directions. Of these, only the lowest order effects of parallel gradients have been previously examined. In addition to higher order gradient terms and curvature effects, collisions are included in a more comprehensive manner. Except for the first order parallel gradients, these physical effects are all mechanisms that cause decorrelation between resonant particles and waves. The relative strength of these decorrelation mechanisms depends heavily on the plasma parameters, and the magnetic field geometry. Methods for determining the dominant decorrelation mechanism based on geometric and plasma parameters are presented. In addition numerical calculations of wave propagation and absorption for a one-dimensional case are performed using a conductivity tensor calculated with these new effects, and the results are compared with those of previous theory.

2C47

Adaptive Optimal Control of RWM in Tokamak

Z.Sun, A.K.Sen and R.W.Longman

Columbia University, New York, NY 10027

As plasma parameters evolve in time during a tokamak discharge, the resistive wall mode growth rate will change and necessitate changes in the feedback circuit parameters. This is especially important for long pulse burning plasma experiments. Motivated by this we have developed an adaptive control system described below. First, we have an online system identification scheme, which continually updates the RWM parameters via either a least square batch method or least square recursive method. The estimated RWM parameters thus determined are fed into a Kalman filter followed by an optimal state feedback design module. The resulting control action will then optimally stabilize the continually updated RWM mode. The fluctuation and control energy are found to be a few times the noise energy. The convergence time for the adaptive control for DIII-D like parameters is found to be 20-30 ms, which may be acceptable.

2C48

Radial Localization And Energetic-Particle Excitation of Alfvén-Ballooning Eigenmodes in High-β Toroidal Plasmas

S. Hu and Liu Chen
Department of Physics and Astronomy, University of California, Irvine

Radial localization of the αTAE, where α measures the plasma pressure gradient, is investigated in the second ballooning stable regime of toroidal plasmas by applying the WKB approximation in the radial direction. The αTAE is a discrete toroidal Alfvén eigenmode trapped in the α-induced potential well due to the ballooning curvature effect and suffers negligible continuum damping even in absence of the toroidal Alfvén frequency gap [*Hu and Chen*, 2004]. Employing the standard ballooning-mode formulation, the two-dimensional eigenvalue problem is reduced into two nested one-dimensional ones: one along the magnetic field line and the other in the radial direction. It is found that the αTAE can indeed be radially bounded around the maximum α, where the corresponding local real frequency is maximized. Resonant excitations by energetic particles are then demonstrated with gyrokinetic-magnetohydrodynamic (MHD) hybrid simulations. While the radial localization of αTAEs is determined by the background MHD plasma, the energetic particle mode (EPM) has much more complicated features; depending on the wave-particle resonances as well as the strength of kinetic instability drive. The detailed stability properties, including the finite radial wavenumber modifications, of the αTAE and the EPM excited by energetic particles will be presented.

Work supported by DOE Grant.

2C49

Symbolic Stability Analysis of Turbulent Fluctuation Data*

A.B. Rechester[1], R.B. White[2]

[1]Institute for Nonlinear Scientific Applications
Sharon, MA 02067

[2]Princeton Plasma Physics Laboratory
Princeton, NJ 08543

Abstract

In the paper [1] we have developed a method for computing stability parameters γ, of symbolic cycles using time record of fluctuating variables X(t). In the present work we are using the same method to compute stability parameter γ averaged over the whole chaotic or turbulent orbit. It appears to be good numerical convergence of this quantity. The main goal of this work is to demonstrate that derivative of γ with respect to the parameter approaches infinity at the turbulent transition point. This could be used as a practical way of diagnosis of turbulent transitions from the analysis of fluctuation data.

As a specific example of turbulent transition we are studying the reverse bifurcation transition in the model of zonal flow [2].

*Work supported by U.S. Dept. of Energy Contract No. DE-FG-0296ER54378.

[1]M. Lehrman and A.B. Rechester, Phys. Rev. Lett **87** 16, 4501 (2001).
[2]L. Chen, Z. Lin, R.B. White, Phys. of Plasmas **7** 3129 (2000).

2C50

Thermal Effects in Intense Laser-Plasma Interactions

B. A. Shadwick,[1,2] G. M. Tarkenton,[2] and E. H. Esarey[1]

[1]Center for Beam Physics, Lawrence Berkeley National Lab, Berkeley, CA 94720. USA
[2]Institute for Advanced Physics, 10875 US Hwy. 285, Suite 199 Conifer, C0 80433, USA

Abstract

Intense laser-plasma interaction experiments access a unique physical regime wherein the plasma electrons experience highly relativistic motion while the temperature (or more correctly, momentum spread) is quite small and the plasma is effectively collisionless. To study this regime, we have recently developed a "warm" fluid model where the width of the distribution function is treated asymptotically. Unlike the collisional case, in this regime the plasma is not in local thermodynamic equilibrium and the pressure tensor can be strongly anisotropic. Using this model, we examine various experimentally relevant configurations, comparing the results of our new model with results of the traditional cold fluid approximation. A case of particular interest which we study in detail is that of a short-pulse pulse propagating in an underdense thermal plasma, where the initial plasma temperature is on the order of 20 eV. Within the quasi-static approximation, the warm-fluid equations for the momentum spread can be solved analytically. We find there is no significant heating of the plasma and that the anisotropy of both the pressure tensor and the distribution function is large. We compare these analytical results to numerical results from both warm and cold fluid models.

On mesoscale plasma pressure perturbations in tokamak

G. Yu and S. I. Krasheninnikov

University of California at San Diego, La Jolla, CA 92093, USA

Strongly localized mesoscale plasma structures with large pressure inhomogeneities (such as plasma blobs in the scrape-off-layer (SOL)/shadow regions, pellet clouds, ELMs) observed in the tokamaks, stellarators and linear plasma devices. Experimental studies of these phenomena reveal striking similarities including more convective rather than diffusive radial plasma transport [1]. We suggest that rather simple models can describe many essentials of nonlinear evolution of plasma pressure perturbation like blobs, ELMs, and pellet clouds dynamics [2]. The main ingredient of these models is the effective plasma gravity caused by magnetic curvature, centrifugal or friction forces effects [3]. As a result, the equations governing plasma transport in such localized structures appear to be rather similar to that used to describe nonlinear evolution of thermal convection in the Boussinesq approximation (directly related to the Rayleigh-Taylor instability). However, "dissipative" terms in the equations describing blobs, pellet clouds, ELMs, and thermal convection are different. In case where dissipation is not important we find that mushroom shape of originally circular blob develops similar to the typical mushrooms shapes in the dynamics of the Rayleigh-Taylor instability. Otherwise, "dissipative" terms can bring structural stability of mesoscale plasma pressure perturbations and they propagate on large distances as coherent structures. We also discuss the phenomenology of 2D Rayleigh-Taylor turbulence (see Ref. 4 and the references therein) and plasma turbulence properties, which follows from our models. These results can be compared with experimental data on ELM statistical properties in the scrape-off layer.

[1] J. A. Boedo, et al., Phys. Plasmas, **8,** 4826 (2001); J J. L. Terry, et al., J. Nucl. Mat., **290-293,** 757 (2001); S. J. Zweben, et al., Phys. Plasmas, **9,** 1981 (2002); E. Sanchez, et al., Phys. Plasmas **7** (2000) 1408; G. Y. Antar, et al., Phys. Plasmas, **10,** 419 (2003); D. L. Rudakov, et al., Plasma Phys. Control. Fusion **44** (2002) 717; G. F. Counsell et al., 19th IAEA Conference, France, 2002, paper IAEA-CN-94/EX/D1-2; V. Rozhansky, et al., Plasma Phys. Control. Fusion **37,** 399 (1995); P. B. Parks, et al., Phys. Plasmas, **7,** 1968 (2000);

[2] S. I. Krasheninnikov, D. D. Ryutov, and G. Yu, To be published in the Journal of Plasma and Fusion Research

[3] S. I. Krasheninnikov, Phys. Letters A, **283,** 368 (2001); D.A. D'Ippolito et al., Phys. Plasmas **9**, 222 (2002); N. Bian, et al., Phys. Plasmas **10,** 671 (2003); S. I. Krasheninnikov and A. I. Smolyakov, Phys. Plasmas, **10,** 3020 (2003).

[4] M. Chertkov, Phys. Rev. Lett. **91** (2003) 115001.

2C52

Simulations of Saturated Tearing Modes in Tokamaks

C.N. Nguyen, G. Bateman, A.H. Kritz

Lehigh University Physics Department
16 Memorial Drive East, Bethlehem, PA, 18015, USA

Abstract

A quasi-linear model, which includes the effect of the neoclassical bootstrap current, is developed for saturated tearing modes in order to compute magnetic island widths in axisymmetric toroidal plasmas with arbitrary aspect ratio, cross-sectional shape, and plasma beta [1]. The theory is derived using three-dimensional scalar plasma pressure force balance, leading to a set of ordinary coupled differential equations. The presence of a magnetic island at each mode rational surface has the effect of locally flattening the pressure and current density profiles, which then results in removing the singularity from the set of coupled differential equations for each helical harmonic of the perturbed magnetic field. Consequently, the set of coupled ordinary differential equations for all the helical harmonics can be integrated from the magnetic axis to the outer boundary conditions. In the resulting algorithm, the widths of the magnetic islands within the plasma are effectively non-linear eigenvalues for the two-point boundary value problem. This quasi-linear technique for determining saturated magnetic island widths has the advantage that any number of geometrically coupled harmonics with different mode rational surfaces can be integrated from the magnetic axis out to whatever boundary conditions are appropriate at the wall. That is, the magnetic island widths are adjusted so that the solution of ordinary differential equations for all the helical harmonics of the helical perturbation satisfies the boundary conditions at the magnetic axis and at the wall. The model is implemented in the BALDUR integrated predictive modeling code. The local enhancements in the transport produced by magnetic islands have a noticeable effect on global plasma confinement in simulations of low aspect ratio, high beta tokamaks, where saturated tearing mode islands can occur with widths that are greater than 15% of the plasma minor radius.

[1] G. Bateman and R.N. Morris, *Physics of Fluids* **29**,753 (1986).

Work supported by U.S. DOE Contract No. DE-FG02-92-ER-5414

2C53

Edge-plasma turbulence simulations with self-consistent profile evolution*

L.L. LoDestro, T.D. Rognlien, M.V. Umansky, X.Q. Xu, and R.H. Cohen
University of California Lawrence Livermore National Laboratory
P.O. Box 808, Livermore, CA 94551 USA

Abstract

Fundamental understanding of plasma transport in the edge region of tokamaks is important to predict and optimize both the formation of edge transport barriers with the associated plasma pedestal and the strong plasma fluxes to material surfaces. Adequate performance of the edge plasma in these areas is crucial for the success of next-step fusion devices. The underlying plasma turbulence and profiles depend strongly on one another. To address this inter-dependency, 3D turbulence simulations with BOUT [1] are evolved together with the axisymmetric (2D) edge profiles. This is accomplished in two ways. In the first, the axisymmetric part of the 3D fields in BOUT is simply allowed to evolve. In the second, the axisymmetric parts of the BOUT fields are controlled: they are evolved on an independent timescale by a UEDGE[2]/BOUT code-coupling scheme. Because the axisymmetric fields evolve on a longer timescale than the 3D dynamics, the coupled scheme has potential for a significant gain in computational efficiency for simulations on the transport timescale. Our initial results on this coupling were reported in [3]. Here we report progress. It is shown that BOUT and UEDGE produce nearly identical 2D plasma profiles for a simple model transport problem, with any differences likely due to variation in the finite-difference approximations. We extend earlier results by including more plasma variables in the coupling. The effect of spatially dependent neutrals as a particle source for the pedestal has been added to BOUT via an analytic neutral source; neutrals are included in UEDGE via a self-consistent fluid neutral component (benchmarked with Monte Carlo). We aim to present multi-field turbulent steady-states with self-consistent radial profiles.

---

*Work performed under auspices of US DOE by University of California Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48 and is supported as LDRD project 03-ERD-009.

[1] X.Q. Xu, R.H. Cohen, T.D. Rognlien, and J.R. Myra, Phys. Plasmas **7** (2000) 1951.
[2] T.D. Rognlien, D.D. Ryutov, N. Mattor and G.D. Porter, Phys. Plasmas **6** (1999) 1851.
[3] T.D. Rognlien *et al.*, Contrib. Plasma Phys., to be pub.; X.Q. Xu *et al.*, *ibid.*

Tuesday evening, April 27

19:30 to 21:30

Doubletree Ballroom

Oral Session 2D

2D01

Gyrokinetic Simulations of Trapped Electron Mode Turbulence in Alcator C-Mod Internal Particle Transport Barriers

D. R. Ernst, P. T. Bonoli, P. J. Catto, W. Dorland,† C. L. Fiore, M. Greenwald, A. E. Hubbard, E. S. Marmar, M. Porkolab, J. E. Rice, and K. Zhurovich

Plasma Science and Fusion Center, Mass. Inst. of Technology, Cambridge, MA, USA
†Department of Physics, Univ. of Maryland, College Park, MD, USA

Mechanisms for internal transport barrier formation and control in Alcator C-Mod are elucidated via nonlinear gyrokinetic simulations of trapped electron mode (TEM) turbulence[1] using the GS2 code.[2] Internal particle transport barriers form in Alcator C-Mod experiments with off-axis RF heating applied near the half-radius, following the transition to EDA H-Mode.[3] During ITB formation, the density profile peaks, keeping the temperature profile unchanged. The density peaking and concomitant impurity accumulation are controlled by injecting low levels of on-axis RF power.[4] We show this is consistent with the temperature dependence arising from gyoBohm scaling of the turbulent transport, with collisionality playing a second order, but additive role.

The critical density gradient for onset of TEM turbulent transport is nonlinearly up-shifted, as shown in Fig. 1. This new nonlinear upshift is analagous to the Dimits shift of the critical ion temperature gradient for toroidal ion temperature gradient driven turbulence,[5] associated with zonal flow generation. The turbulent particle diffusivity from GS2 gyrokinetic simulations matches the particle diffusivity from transport analysis, within experimental error bars, after accounting for the Ware pinch. Further, the TEM turbulent particle flux and the Ware pinch are in balance in the ITB. The simulated one-fluid thermal diffusivity matches the TRANSP experimental value. With no core particle source and high-resolution density diagnostics, the C-Mod experiments provide a nearly ideal test bed for particle transport studies. The electron continuity equation simply expresses the balance between the neoclassical (Ware) and turbulent fluxes, $\partial n_e/\partial t + \nabla \cdot (n_e V_{\rm Ware} - D_{\rm eff}\nabla n_e) = 0$, where $\Gamma_{\rm Ware} = n_e V_{\rm Ware}$ is the Ware flux.

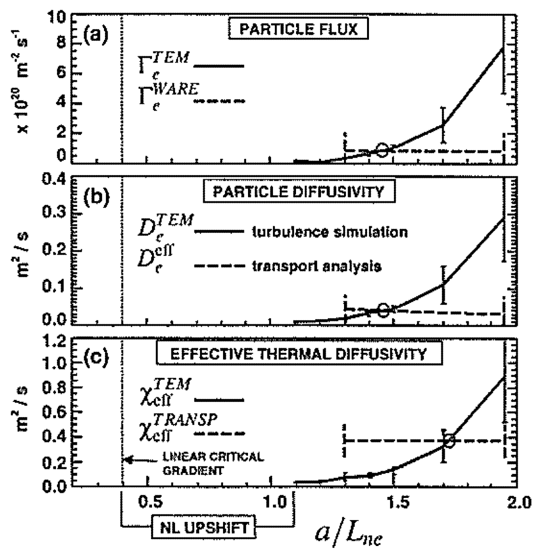


Figure 1: In the ITB at $\rho = 0.4$, 1.20 sec. (a) Simulated particle flux balances Ware pinch within error bars (representing uncertainty in the $Z_{\rm eff}$ gradient) (b) Simulated turbulent diffusivity matches transport analysis within error bars. (c) Simulated effective one-fluid thermal diffusivity matches TRANSP. Nonlinear critical density gradient is upshifted relative to linear threshold.[1]

[1] D. R. Ernst *et al.*, Paper UI1 5, Bull. Am. Phys. Soc. **48**, 332 (2003). To appear in Phys. Plasmas.
[2] W. Dorland, E. Jenko, M. Kotschenreuther, and B. N. Rogers, Phys. Rev. Lett. **85**, 5579 (2000).
[3] C. L. Fiore *et al.*, Paper UI1 4, Bull. Am. Phys. Soc. **48**, 331 (2003). To appear in Phys. Plasmas.
[4] S. J. Wukitch *et al.*, Phys. Plasmas **9**, 2149 (2002).
[5] A. M. Dimits *et al.*, Phys. Plasmas **7**(3) 969 (2000).

2D02

A simple model of interactions between electron temperature gradient and drift-wave turbulence

C. Holland[1,2], P. H. Diamond[2]

[1] Dept. of Mechanical and Aerospace Engineering, University of California, San Diego, San Diego, CA 92117

[2] Dept. of Physics, University of California, San Diego San Diego, CA 92117

Abstract

One of the key challenges in magnetic confinement research is to understand the underlying causes of anomalous particle and heat transport. In most theories and models of turbulent transport, there is assumed to be one dominant kind of instability which is taken as the sole driver of all of the transport channels. In reality, multiple instabilities on different scales may coexist (i.e. ion temperature gradient-driven drift-waves (DITG) on $\rho_s = C_s / \Omega_{ci}$ scales, and electron temperature gradient (ETG) driven modes on $\rho_e = V_{Te} / \Omega_{ce}$ scales). Previously, it has been argued (or more often, tacitly assumed) that the separation in temporal and spatial scales meant that interactions between instabilities on different scales were generally negligible relative to the nonlinear "self" interactions of a particular instability. However, with the rise in interest in the ETG mode as a source of electron heat transport, and given the possibility of the simultaneous presence of DITG turbulence, it is important to consider their interactions in a more quantitative fashion. This question is particularly important as much of the motivation for ETG-based transport models has arisen from arguments about the presence of large (relative to ρ_e) structures driven by the ETG turbulence, such as "streamers" or electron skin depth (c / ω_{pe}) scale eddies, which reduce the effective scale separation between the ETG and DITG turbulence. Towards this end, a self - consistent theory for the interaction between ETG and DITG turbulence has been developed. Random shear suppression of ETG turbulence by DITG modes is studied, as well as the back-reaction of the ETG modes on the DITG turbulence via stresses. It is found that the large-scale ETG dynamics can be sensitive to shearing by short-wavelength DITG modes (such as trapped electron modes). A novel interaction mechanism, DITG modulations of the electron temperature gradient, is shown to be quite significant, particularly as it opposes the shearing effects of the DITG turbulence. The profile modulation interaction also points toward the possibility of a rich spectrum of nonlinear spatio-temporal interactions between ETG and DITG turbulence. Of particular interest is the possibility that the DITG profile modulations could lead to a strong increase in the intermittency or "burstiness" of the ETG-driven heat flux. Conversely, the back-reaction of the ETG on the DITG turbulence is found to be weak. A generalized predator-prey model that incorporates the different cross-mode interactions has been developed. The importance of different interactions is quantified via scalings which sensitively depend upon the electron - ion mass ratio; in particular, it is shown that different interactions have different mass-ratio scalings. The implications of these findings for the relevance of ETG-driven transport, particularly in transport barriers, is discussed, along with potential avenues for further quantifying the strength of cross-mode interactions.

2D03

Formation and Instability of Phase Space Structures

D. Yu. Eremin and H. L. Berk

Institute for Fusion Studies,
The University of Texas at Austin,
Austin,Tx. 78712

Abstract

Near marginal stability of a kinetic system, when an instability drive of a kinetic distribution is in near balance with background dissipation, spontaneous phase space structures can develop in the form of holes and clumps[1] that support nonlinear waves. These waves are similar, but more general than Bernstein, Greene, Kruskal waves, as they can occur in a complex geometry (such as a global mode in a tokamak) . The theory used has a universal character, and predictions from the paradigm, bump-on-tail problem, for which numerical simulation is straight forward, can be applied to more complex problems. Background dissipation induces frequency sweeping from the changing velocity of these structures, and experimentally observed sweeping signals suggest that these structures may be responsible for frequency sweeping observed in several experiments. The observation of how much the frequency shifts in a given time may even be the basis of a diagnostic to determine the magnitude of the internal fields[2]. Once a phase space structure is formed, the dynamics of the phase structures can be followed accurately using a self-consistent theory for the adiabatic evolution of both the particles and the wave. However, the adiabatic evolution may eventually reach a point where this theory intrinsically breaks down: either because the termination of frequency sweeping is predicted which would then imply the breakdown of the adiabatic assumption, or because the adiabatic evolution equations reach a singular point where the equations can no longer make a unique prediction[3]. The kinetic linear instability analysis of the nonlinear wave supported by the phase space structure will be discussed here. It is shown that these "difficult" points are precisely the marginal points for linear instability of the structure when the wavelength of the perturbation is identical with the wavelength of the nonlinear mode (note that geometrical considerations can prevent the excitation of sideband instabilities where the unstable wavelengths differs from the wavelength of the nonlinear wave, but here we have shown that instability cannot be avoided when the adiabatic theory becomes internally inconsistent or non-predictive). A simulation with a delta-f particle code shows that the adiabatic theory is quite accurate to the point of instability. Then instability is triggered and in the nonlinear phase coherent oscillations arise. After they damp, it is found that phase space structures still survive at a somewhat smaller size and frequency sweeping continues, albeit at a slower rate.

[1] H.L. Berk, B.N. Breizman, J. Candy, M.S. Pekker, N.V. Petviashvili, Phys. Plasmas **6**, 3102 (1999)

[2] S. D. Pinches, H. L. Berk, M. P. Gryaznevich, M. S. Sharapov "Spectroscopic Determination of the Internal Field Amplitude of Frequency Sweeping TAE" Preprint: EFDA-JET-PR(03) 58,(2003) submitted to Plasma Physics and Controlled Fusion

[3] D. Yu. Eremin and H. L. Berk Phys. Plasmas **9**, 772, (2002)

Acceleration of charged particles by crossing RF or micro waves in an external magnetic field, Resonant Moments Method (RMM)

Maxim Ponomarjov and Daniele Carati

Statistical and Plasma Physics, EURATOM Assoc. - Belgium State, CP 231,
Campus Plaine, Universite Libre de Bruxelles, 1050 Brussels, Belgium

Abstract

A mechanism for enhanced acceleration of charged particles using crossing radio frequency or micro waves propagating at different angles with respect to an external magnetic field is investigated. This mechanism consists in introducing low amplitude secondary waves in order to improve the parallel momentum transfer from the high amplitude primary wave to charged particles. In Refs. [1-2] it has been pointed out that it may be more effective to accelerate electrons when the waves propagate obliquely to the external magnetic field. The idea considered here is similar although no constraint is imposed on the refraction indices of the primary and the secondary waves.

The theoretical analysis of the acceleration mechanism is based on the Resonance Moments Method (RMM) in which moments of the velocity distribution are computed by using an average over the resonant layers $(RL)_i$ only instead of a complete phase-space average. The quantities obtained using this approach, referred to as Resonant Moments (RM), suggest the existence of optimal angles of propagation for the primary and secondary waves as long as the maximization of the parallel flux of charged particles is considered The secondary wave tends to maintain a pseudo-equilibrium velocity distribution by continuously re-filling the RL. Indeed, the combined effect of the two-waves and the magnetic field yields a stochastic motion which, though very different in nature, have some similar consequences as a collisional thermalisation of the particles population. Moreover, the synchronization between the waves and the gyro-motion of the particles is, on average, more favorable for transferring momentum to the particles.

Our suggestions are confirmed by direct numerical simulations of particle trajectories for a populations of 10^5 electrons. The parameters for these simulations are relevant in today tokamak plasma. In particular, the primary wave corresponds to the second harmonic of the cyclotron frequency and the secondary wave to the third harmonic extraordinary mode which are used for instance in the TCV tokamak experiments [3]. Our simulations confirm that the secondary perpendicular wave is the most effective for a stochastization of the particles trajectories and, consequently, to maintain a pseudo-equilibrium. Although measures of the distributions clearly show a departure from a thermal equilibrium, the stochastization effect of the secondary wave yields a clear increase (up to one order of magnitude) of the average parallel velocity of the particles. It is a quite promising result since the amplitude of the secondary wave is ten times lower the one of the first wave.

[1] H. Karimabadi and V. Angelopoulos, Phys. Rev. Lett., 62, 2342 (1989).
[2] B. I. Cohen, R. H Cohen, W. M. Nevins, and T. D. Rognlien, Rev. Mod. Phys., 63, 949 (1991).
[3] S. Alberti, T.P. Goodman, M.A. Henderson, A. Manini, J.-M. Moret, P. Gomez, P. Blanchard, S. Coda, O. Sauter, Y. Peysson, TCV Team, Nucl.Fusion, 42, 42 (2002).

Wednesday morning, April 28

8:30 to 9:30

Doubletree Ballroom

Review Talk 3A

3A01

ELM Energy/Particle Plasma Losses and Fluxes on Plasma Facing Components

Alberto Loarte

EFDA-Close Support Unit Garching
Max-Planck-Institut für Plasmaphysik
D-85748 Garching bei München, Germany

Energy fluxes caused by Type I ELMs in next step tokamak devices may lead to energy fluxes on Plasma Facing Components (PFCs) which limit their lifetime due to the associated evaporation and/or melting. Systematic studies to characterise the loss of energy and particles and their transport to PFCs have been carried out in all major divertor tokamaks and have provided a common qualitative/quantitative picture of the processes involved in the transport of energy during ELMs. Despite this common picture, the detailed understanding of these processes in terms of the various physics mechanisms involved is far from complete :

a) The size of the ELM energy loss is intrinsically related to the mechanisms involved in ELM energy transport (smaller ELMs are observed when the dominant mechanism for transport is convection) but not to the volume in which the plasma parameters collapse at the ELM. This indicates that there is not a simple relation between characteristics of the ELM MHD trigger and the ELM energy loss, as initially proposed within the peeling-ballooning model picture of the ELM.

b) The transport of energy from the bulk plasma to the PFCs (divertor and main chamber limiters) seems to be correlated with the dominant transport mechanism for main plasma ELM energy loss. More conductive ELMs lead to a large proportion of the ELM energy flowing to the limiters than to the divertor targets, which is consistent with the measured large radial propagation velocities (~ 1 km/s) of the density perturbation in the SOL caused by the ELMs.

The paper will review the experimental evidence behind the above observations and will discuss their interpretation in terms of present models for the ELM collapse and suggest areas where theoretical/modelling developments for the understanding of Type I ELMs are required.

Wednesday morning, April 28

10:00 to 12:00

Doubletree Ballroom

Oral Session 3B

3B01

Experimental and Theoretical Studies of Electrostatic Confinement on the INS-e Device

R. A. Nebel, J. Park, L. Chacon, S. Stange, M. Taccetti

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Abstract

Theoretical studies[1,2] have suggested that a tiny oscillating ion cloud immersed in a uniform electron background may undergo a self-similar collapse that can result in the periodic and simultaneous attainment of ultra-high densities and temperatures. The oscillating ion cloud (referred to as the Periodically Oscillating Plasma Sphere or POPS) is in local thermodynamic equilibrium at all times independent of the collisionality of the plasma (i.e. these self-similar solutions are exact solutions of the Vlasov equation). POPS is stable to multidimensional perturbations, while its self-similar solutions appear to be attractors.[3] Theoretical projections have indicated that such a system may have net fusion gain even for an advanced fuel such as D-D. In addition, these systems have very favorable reactor attributes in that the total power scales inversely with the size, leading naturally to a modular, high mass power density device.

However, there are several issues that need to be resolved in order to determine the efficacy of this scheme. In particular, POPS requires a quiet virtual cathode with a harmonic potential well, which calls for control of the plasma density profile and its stability. A deep, steady-state potential well has been created in our electrostatic device without any apparent sign of instability.[4] It has also been shown that the radial electron density profile can be varied to produce a desired near-uniform density by adjusting the bias voltages of the grids. Virtual cathode well depths as deep as 60% of the applied voltage have been achieved experimentally, exceeding the theoretically predicted stability limits[5] by a factor of 4. In order to understand this discrepancy, new theoretical work has been undertaken using the ENNF code, a 1-D gridless PIC simulation code. Results indicate that in spherical geometry the two-stream stability limit allows virtual cathodes with well depths close to 100% of the applied voltage.

We are also using the code to do fully kinetic (ions and electrons) studies of POPS in order to study space charge effects during the ion collapse phase. An analytic formalism has shown that it is possible to program the distribution function of the injected electrons to completely mitigate space charge effects during the ion cloud collapse. If this can be achieved, the required compression rations for POPS can be drastically reduced. These results are presently being tested with the simulations.

1. R. A. Nebel, D. C. Barnes, Fusion Technology 38, 28 (1998).
2. D. C. Barnes, R. A. Nebel, Physics of Plasmas 5, 2498 (1998).
3. R. A. Nebel, J. M. Finn, Physics of Plasmas 7, 839 (2000).
4. J. Park, R. A. Nebel, W. G. Rellergert, M. D. Sekora, Physics of Plasmas 10, 3841 (2003).
5. R. A. Nebel, J. M. Finn, Physics of Plasmas 8, 1505 (2001).

3B02

Influence of pressure-gradient and shear on ballooning stability in stellarators

S.R.Hudson[1], C.C.Hegna[2], N.Nakajima[3], R.Torasso[4], A.S.Ware[5]
1) Princeton Plasma Physics Laboratory, P.O. Box 451,Princeton NJ 08543, USA.
2) Department of Engineering Physics, University of Wisconsin–Madison, WI 53706, USA.
3) National Institute for Fusion Science, Nagoya 464-01, Japan.
4) Courant Institute of Mathematical Sciences, New York University, NY 10012, USA.
5) Department of Physics and Astronomy, University of Montana, Missoula, MT, 59812, USA.

A simple, semi-analytic method for expressing the ballooning growth rate as functions of the pressure-gradient and the averaged magnetic shear is introduced. For a given configuration, the the ballooning equation is written $[\partial_\eta P \partial_\eta + Q - \lambda \sqrt{g}^2 P]\xi = 0$, where the ballooning coefficients $P = B^2/g^{\psi\psi} + g^{\psi\psi} L^2$ and $Q = 2p'\sqrt{g}(G + \iota I)(\kappa_n + \kappa_g L)$. Here L is the integrated local shear, $L = \int_{\eta_k}^{\eta} s(\eta')d\eta'$, where $s = \iota' + \tilde{s}$ is the local shear, and κ_n, κ_g represent the normal and geodesic curvatures. This is an eigenvalue equation and for realistic geometry must be solved numerically.

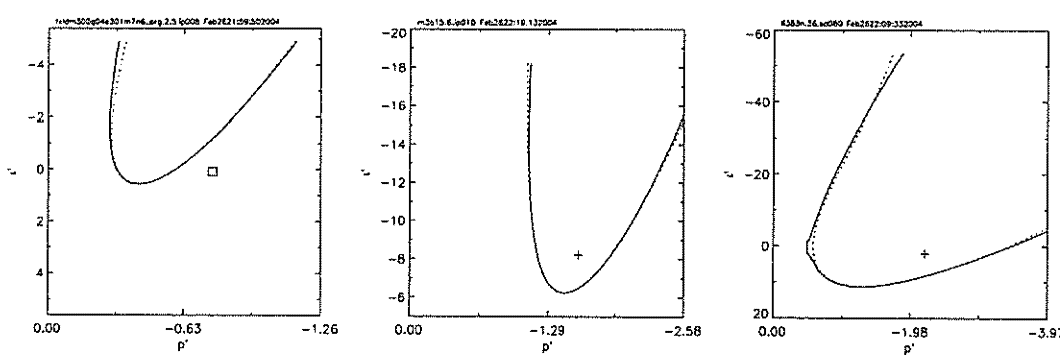
An analytic variation in the pressure-gradient, $p' \to p' + \delta p'$, and average shear, $\iota' \to \iota' + \delta\iota'$, is imposed at an arbitrary flux surface of an MHD equilibrium. The relevant equilibrium quantities are then adjusted to preserve force balance. The variations $(\delta p', \delta\iota')$ alter the ballooning coefficients, $P \to P + \delta P$, $Q \to Q + \delta Q$, and the impact of the variations on the ballooning growth rate may be determined using eigenvalue perturbation theory. An expression for the change in the ballooning eigenvalue can be derived

$$\lambda(\delta p', \delta\iota') = \lambda_o + \frac{\partial\lambda}{\partial p'}\delta p' + \frac{\partial\lambda}{\partial\iota'}\delta\iota' + \frac{\partial^2\lambda}{\partial p'^2}\delta p'^2 + \frac{\partial^2\lambda}{\partial p'\partial\iota'}\delta p'\delta\iota' + \frac{\partial^2\lambda}{\partial\iota'^2}\delta\iota'^2 + \ldots, \qquad (1)$$

where λ_0 is the eigenvalue of the original equilibrium and explicit expressions for the derivatives, up to arbitrary order, are determined from a *single eigenfunction calculation.* Using only this information, whether increased pressure-gradient is stabilizing or de-stabilizing, and the existence of a second stable region, can be determined.

Marginal stability diagrams for an LHD-like configuration (left), a quasi-poloidal configuration (center) and an NCSX-like quasi-symmetric configuration(right) are presented in the figure below. The solid line shows the exact calculation: that is, the eigenvalue equation is resolved numerically for each variation $(\delta p', \delta\iota')$ on a grid of 200×200 points; and the dotted line shows the approximation provided by Eqn.(1). Also shown is the location in (p', ι') space of the original equilibrium, indicated with a '+' if that equilibrium is unstable or a '□' if it is stable.

The analysis presented here provides both a numerically efficient and physically insightful approach to determining second stability in stellarators.



3B03

Two-Fluid Performance Limits: Stellarator and Tokamak Compared

L.E. Sugiyama[1], H.R. Strauss[2], W. Park[3], G.Y. Fu[3]

[1] Massachusetts Institute of Technology
Cambridge MA 02139

[2] Courant Institute of Mathematical Sciences, New York University
New York, NY 10012

[3] Princeton Plasma Physics Laboratory
Princeton NJ 08543

Abstract

Stellarator plasmas have generated a number of puzzling observations that resist explanation by the MHD model, in contrast to its success in axisymmetric configurations. Studies with the M3D initial value code show that basic nonlinear two-fluid effects[1], those required beyond MHD to generate the self-consistent diamagnetic drifts of the electrons and ions, relax the major MHD limits on stellarator performance. For the NCSX stellarator, ion FLR and other effects robustly stabilize the most limiting ideal MHD ballooning modes above a certain moderate-to-high mode number and also stabilize resistive MHD ballooning and interchange modes at their most unstable, moderate-to-high mode numbers. Two-fluid models also predict the importance of a "soft" beta limit at high electron β_e, where magnetic islands grow large enough to reduce thermal and plasma confinement and prevent further plasma heating, due to the electron pressure parallel gradient $\nabla_{\parallel} p_e/(en)$ in Ohm's law. This effect is stronger in stellarators than axisymmetric plasmas, since magnetic islands are driven differently in the two configurations. Neglecting neoclassical stresses, growing tokamak islands rotate, while stellarator islands do not. Existing models of flow effects on island growth (polarization current) do not explain the results. Disagreement arises from the analytical neglect of the two-fluid global steady state conditions and from differences in the actual, compared to the assumed, plasma island evolution. In both configurations, the two-fluid global steady state differs significantly from MHD. The $\nabla_{\parallel} p_e/(en)$ term and the ion gyroviscous (IGV) stress introduce effects similar to the parallel "momentum damping" of the neoclassical parallel collisional stresses. They drive a global steady state radial electric field E_r, which reverses sign at high p_e/p rather than at low collisionality like the neoclassical field. The ion fluid poloidal velocity $v_{i\theta}$ is significantly damped.

[1] L.E. Sugiyama and W. Park, *Phys. Plasmas* 7 4644 (2000).

Resistive wall mode in quasi-stationary collisionless plasmas

Riccardo Betti, Bo Hu and Luca Guazzotto

Laboratory for Laser Energetics, University of Rochester
Rochester, NY 14623

Abstract

According to standard ideal magnetohydrodynamic (MHD) theory, the resistive wall mode (RWM) is a macroscopic instability of tokamak plasmas that limits the maximum achievable beta. The RWM is an external kink driven unstable by the finite electrical resistivity of the metal wall surrounding the plasma. Theories and experiments have shown that the RWM can be stabilized by a combination of fast plasma rotation and dissipation. The fast toroidal rotation is induced by neutral beam injection and its magnitude is a significant fraction of the sound speed. However, reactor-sized plasmas without powerful neutral beams such as ITER's (International Thermonuclear Experimental Reactor) are expected to be stationary or rotate with velocities much slower than the sound speed. Even with active feedback control, the RWM in ITER may not be fully suppressed since the feedback coils are external to the first wall and vacuum vessel. However, standard ideal MHD theories may not correctly predict the stability properties of collisionless plasmas such as ITER's. In this work, we have investigated the stability of the RWM in the ITER-relevant collisionality regime and found that the RWM could be fully suppressed even in the absence of plasma rotation. The stabilization occurs because of the interaction of the mode with the precession drift motion of the trapped thermal ions. Since the RWM magnetic perturbation needs to diffuse through the wall, its mode frequency in the wall frame of reference is negligible with respect to all the other relevant plasma frequencies. It follows that the mode Doppler-shifted frequency in the $\boldsymbol{E} \times \boldsymbol{B}$ drift frame of reference is approximately equal to $\omega_d \simeq -\omega_E = -E_r/(RB_\theta)$ and it can resonate with the trapped particle magnetic drift frequency ω_B. In the absence of flow, the ion equilibrium requires that $\omega_E \simeq -\omega_{*i}$ and the mode-particle interaction is found to be quite strong. The non-resonant particle contribution counteracts the fluid instability drive while the resonant interaction dissipates energy to the trapped particles. The electrostatic terms also play an important role and enhance the kinetic effect. The kinetic effect is included through a sharp boundary model of toroidal plasma keeping the leading order poloidal coupling [1] yielding an algebraic eigenvalue problem. Numerical results [2] from this sharp boundary model show that ITER-like collisionless plasmas could be stable up to the ideal-wall beta limit in the absence of toroidal rotation. This effect is significantly reduced for rotation frequencies much greater than ω_{*i} and it is not expected to play a major role in fast rotating plasmas. This work is supported by the U.S. Department of Energy under Contract No. DE-FG02-93ER54215.

[1] R. Betti, Phys. Plasmas 5, 3615 (1998).
[2] B. Hu and R. Betti, submitted to Phys. Rev. Lett.

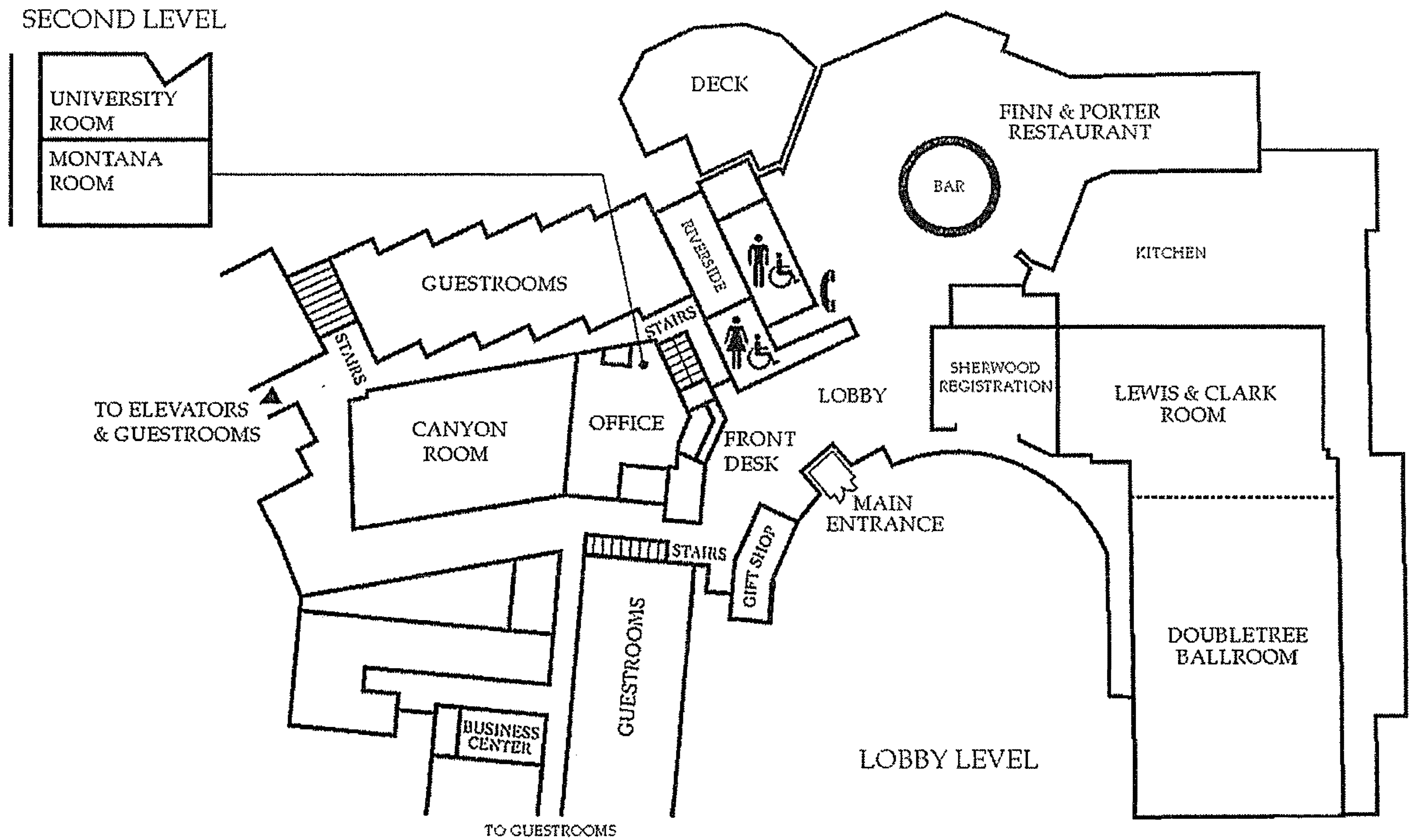
Author Index

Author Index

Author Index

Author Index

Author Index



· All Oral Sessions to be held in the DOUBLETREE BALLROOM.
· All Poster Sessions to be held in the LEWIS & CLARK ROOM.
· Computers for checking email are available in the RIVERSIDE ROOM.
· Satellite meetings will be held in the UNIVERSITY, MONTANA, and CANYON ROOMS.

Monday, April 26

08:20. Welcome: Andrew Ware, Local Organizing Committee, Doubletree Ballroom, Doubletree Hotel Missoula, Lobby Level

08:30. Review Talk 1A. Climate Change: What Do We Really Know? *Inez Fung*
Chair: Lynda Lodestro

09:30. Oral Session 1B. Non-Diffusive Transport in Plasma Turbulence: A Fractional Diffusion Approach. *Diego del-Castillo-Negrete*
Chair: Lynda Lodestro

10:00. Poster Session 1C.
Coffee Break during Poster Session.

12:00. Lunch

Oral Session 1D. Chair: Alan Glasser

13:30. Extending the Peeling-Ballooning Model of ELMs: Toroidal Rotation and 3D Nonlinear Dynamics. *Phil Snyder*

14:00. Non-Curvature Driven Modes in the Edge Pedestal. *Barrett Rogers*

14:30. A Model of the Radiatively Improved (RI) Confinement Mode in Tokamaks. *Predimin Kaw*

15:00. Dynamics of Dust Motion in Tokamak Edge Plasmas. *Sergei Krasheninnikov*

15:30. Poster Session 1E.
Coffee/Beverage Break during Poster Session

Tuesday, April 27

08:30. Review Talk 2A. Astrophysical Dynamo Action. *Fausto Cattaneo*
Chair: Chris Hegna

9:30. Oral Session 2B. Astrophysical Magnetic Helicity Injection: Jets, Lobes, and LAPD-U. *Xianzhu Tang*
Chair: Chris Hegna

10:00. Poster Session 1C.
Coffee Break during Poster Session.

12:00. Lunch—Free Afternoon

18:00. Conference Dinner. Doubletree Hotel Missoula, Doubletree Ballroom, Lobby Level

Oral Session 2D. Chair: Glenn Bateman

19:30. Gyrokinetic Simulations of Trapped Electron Mode Turbulence in Alcator C-Mod Internal Particle Transport Barriers. *Darin Ernst*

20:00. A Simple Model of Interactions Between Electron Temperature Gradient and Drift-Wave Turbulence. *Christopher Holland*

20:30. Formation and Instability of Phase Space Structures. *Denis Eremin*

21:00. Acceleration of Charged Particles by Crossing RF or Micro Waves in an External Magnetic Field, Resonant Moments Method (RMM).
Maxim Ponomarjov

Wednesday, April 28

8:30. Review Talk 3A. ELM Energy/Particle Plasma Losses and Fluxes on Plasma Facing Components.
Alberto Loarte
Chair: Andrew Ware

9:30. Coffee Break

Oral Session 3B. Chair: Scott Parker

10:00. Experimental and Theoretical Studies of Electrostatic Confinement on the INS-e Device.
Rick Nebel

10:30. Influence of Pressure-Gradient and Shear on Ballooning Stability in Stellarators. *Stuart Hudson*

11:00. Two-Fluid Performance Limits: Stellarator and Tokamak Compared. *Linda Sugiyama*

11:30. Resistive Wall Mode in Quasi-Stationary Collisionless Plasmas. *Riccardo Betti*